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Pilot Scale Investigation of Dissolved Air Flotation Performance for Drinking Water Treatment: An Evalutation of Process Parameters

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ABSTRACT

The West River Treatment Plant (WRTP) is a 10.2 million gallon per day in-line direct filtration plant. Pilot scale studies have been performed at the WRTP since 1989 to evaluate treatment alternatives to meet changing regulations and to explore a possible plant expansion. Dissolved Air Flotation (DAF) was evaluated during 1992 in a pilot train consisting of ozonation (either pre- or intermediate-), two stage flocculation, flotation, and filtration. The DAF train was studied as a method of plant expansion whereby solids removal by DAF would allow for increased hydraulic loading rates to the filters. The effects of several DAF train process parameters on flotation and filtration performance were evaluated. DAF performance was compared in parallel to a direct filtration train consisting of pre-ozonation, rapid mix and filtration.

Dissolved air flotation followed by filtration provided effective overall treatment with respect to finished water quality and filter performance. Finished water quality for the DAF train was similar to the parallel direct filtration train as measured by turbidity, ultraviolet absorbance at 254 nm, dissolved organic carbon, and particle counts. Solids removal by DAF resulted in filter run times three times longer than for the direct filtration train at the same filter hydraulic loading rate. DAF provided effective treatment with reasonable headloss development at increased filter hydraulic loading rates.

Results are presented from studies evaluating variations in several DAF train process parameters. DAF provided effective treatment using both ferric chloride with a cationic polymer and ferric chloride alone as primary coagulants. DAF performed

well at recycle ratios of 9.5 and 8.0 percent but clogging of the needle valves at 6.0 and 5.0 percent recycle resulted in less effective particulate removal. Intermittent operation of a full length mechanical scraper for sludge removal was effective at frequencies of one time per hour to one time per eight hours. Flocculation times of both 16 and 8 minutes resulted in effective flotation performance. Pre-ozonation resulted in effective treatment throughout 1992. However, intermediate ozonation (after flotation) on the DAF train produced mixed results with oxidation and subsequent precipitation of manganese producing high filtered water turbidity.

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CHAPTER I

1. INTRODUCTION AND BACKGROUND

1.1 Introduction

Dissolved air flotation (DAF) is becoming an increasingly popular approach to solid-liquid separation in drinking water treatment for both existing plant upgrades and new plant designs. In the DAF process, recycled water (6 to 12 percent of either clarified or filtered water) is pressurized, saturated with air and injected into the bottom of the float tank through nozzles or needle valves. The pressure drop across the nozzles results in the release of fine bubbles that attach to destabilized particles in the water. The bubble-particle agglomerates rise to the surface where they are subsequently removed. Some of the common reported advantages of DAF are: 1) efficient removal of algae; 2) good treatment of low-turbidity, soft, highly colored waters; 3) high surface loading rates; and 4) high sludge solids concentrations (Zabel, 1985; Janssens, 1990). Janssens (1990) and Edzwald and Malley (1990) also report that the pin-point floc required for flotation allow for shorter flocculation times than the flocculation time required for sedimentation.

1.2 Statement of the Problem

The West River Treatment Plant (WRTP), owned and operated by the South Central Connecticut Regional Water Authority (SCCRWA), is a 10.4 million gallon per day (mgd) in-line direct filtration plant. In order to continue to meet changing regulations, and to explore a possible plant expansion, the SCCRWA has been conducting pilot scale studies of alternative treatment processes at the WRTP for several years.

Work conducted prior to 1992 investigated the impacts of pre-oxidation with ozone or hydrogen peroxide and ozone (peroxone) and biologically active filtration on water quality during in-line direct filtration. The work focused on the fate of organic carbon, the microbiological regrowth potential at different locations and the formation of disinfection by-products (DBPs) following post-filtration disinfection using free chlorine.

Work conducted during 1992 investigated three treatment alternatives: 1) pre-ozonation and biologically active in-line granular activated carbon (GAC)/sand dual media direct filtration, 2) ozonation of WRTP filtered water followed by a biologically active GAC monomedia contactor and 3) treatment utilizing pre- or intermediate-ozone, dissolved air flotation and GAC/sand dual media filtration. Routine monitoring focused on the fate of organic matter, measured by dissolved organic carbon, assimilable organic carbon, and chlorinated DBP precursors. Also, during the summer and fall of 1992, extensive testing was performed on the DAF train to evaluate the effects of changing process variables on general water quality and filtration performance. DAF was studied as a method of plant expansion where solids removal by DAF would allow for an increased filter hydraulic loading at the WRTP and therefore increased plant capacity.

1.3 Research Objectives

The primary goals of this research were to study the effectiveness of DAF for treatment of WRTP source water and to optimize flotation and filtration following flotation. The specific objectives of this work included:

1) To study the effectiveness of DAF for treatment of the WRTP source water as measured by water quality parameters (turbidity, ultraviolet absorbance at 254 nm (UV254), particle counts, and dissolved organic carbon (DOC)) and headloss development.
2) To compare DAF to direct filtration (DF) with regard to finished water quality and filter performance.
3) To evaluate the effects of several process variables of the DAF train on flotation and filtration (following flotation) performance. Variables included coagulant type, recycle, filter loading rate, flocculation time, sludge removal and location of ozonation.

1.4 Scope of Work

The pilot trains at West River were continuously operated by SCCRWA personnel and University of Massachusetts (UMass) students during 1992. Filtered water turbidity and UV254 and unit filter run times (based on run time to eight feet of headloss) were monitored daily to evaluate general performance of the pilot trains. More extensive monitoring, including turbidity, UV254, pH, particle counts, DOC, assimilable organic carbon (AOC), total trihalomethane formation potential (TTHMFP) and the sum of five haloacetic acid formation potentials (HAA5FP) at multiple locations along the pilot trains, was conducted six to seven times during the year to help further evaluate performance.

Twenty experiments (denoted here as "runs") were performed on the DAF train during the summer and fall of 1992 to evaluate different process parameters. A run started with a filter backwash and was continued until 1) water quality breakthrough (filtered turbidity greater than 0.15 ntu or UV254 removal over the entire train below 50%), or, 2) eight feet of headloss was reached or, 3) 12 hours had passed. Turbidity, UV254, and filter headloss were measured every half hour for the DAF train filtered waters. For some runs the same parameters were measured for the direct filtration train. For other runs, the turbidity of the DAF effluent (clarified water) was measured every half hour. Also, turbidity, UV254, and pH were measured three or four times per run at all sample locations along the DAF train and, when appropriate, also along the direct filtration train. DOC samples and particle counts were taken twice at all sample locations for each run.

CHAPTER II

2. LITERATURE REVIEW

This chapter contains a brief review of published research on dissolved air flotation, ozonation, and direct filtration.

2.1 DAF in Water Treatment

2.1.1 Introduction

Flotation processes, including dispersed air flotation, dissolved air flotation and electrolytic flotation, have been used for more than 100 years, first for separation of mineral ores and later for treatment of industrial waste. Dissolved air flotation has historically been used to separate suspended solids, oils and greases, fibers and other low density materials from various liquids. More recently, dissolved air flotation has been used for thickening of activated sludge and treatment of drinking water (Janssens, 1990).

Zabel (1985) provides an extensive review of flotation processes currently in use. The three main types of flotation are: dispersed air flotation, dissolved air flotation and electrolytic flotation. Dispersed air flotation is not suitable for generation of potable water for the following reasons: 1) it generates relatively large bubbles compared to the other methods; 2) it creates high amounts of turbulence or shear, which would break up floc formed during chemical treatment; and 3) addition of surfactants which are unacceptable in drinking water is required to produce sufficiently small bubbles. Electrolytic flotation is not generally used for drinking water treatment because dissolution of the electrodes required for the process causes heavy metal contamination. Other disadvantages of electrolytic flotation are low surface loading rates and electrode maintenance problems.

The three types of dissolved air flotation are vacuum flotation, micro-flotation and pressure flotation. The most common type utilized today for treatment of drinking water is pressure flotation, which can be performed by full-flow pressure flotation, split-flow pressure flotation or recycle-flow pressure flotation. In full-flow and split-flow, either all (full-flow) or part (split-flow) of the influent is subjected to pressurization. Full- and split-flow dissolved air flotation are generally unsuitable for potable water treatment because pressurization of the influent destroys floc required for treatment. Pressure dissolved air flotation utilizing recycle flow (DAF) is the most common method of flotation used in drinking water treatment today and is described below.

Treatment of potable water by DAF started in the 1960's and at present has been applied in South Africa, Australia, North America and throughout Europe (for example: the United Kingdom, the Netherlands, Belgium, Scandinavia, and Scotland). Heinänen, *et al.* (1992) reported on 36 drinking water plants in Finland which utilize DAF. According to Heinänen, Finnish raw waters are usually clear, humic, and have low temperatures over a long period of time, and are therefore very treatable by DAF. Schers and van Dijk (1992) reported that as of 1991, five Dutch and one Belgian plant used DAF. Olsen (1993), reported six operating full scale DAF water treatment plants in the United States and another five in the planning, design or construction phase.

A schematic of a typical DAF water treatment plant is shown in Figure 2.1. Treatment by DAF begins with chemical addition and rapid mixing followed by flocculation. From the flocculation basin, water flows directly into the bottom of the flotation basin at the point of recycle injection. Recycle flow, taken either after flotation or filtration, is supersaturated with air at a pressure of 50-90 psig in a saturator vessel. Upon injection to the flotation unit, the flow is released to atmospheric pressure causing formation of small bubbles in the range of 10 to 100 μm in diameter (Zabel, 1984). As they rise, bubbles attach to destabilized particles (flocculation particles) producing low density particle-bubble agglomerates that float to the water surface. Following flotation the water is filtered and sent to subsequent treatment. The sludge (float) collects on the water surface and is periodically removed by mechanical scrapers, rollers or flooding of the tank.

Table 2.1 contains typical design and operational parameters of existing DAF plants as compiled by Bunker (1993) from Walsh (1991) and Tamulonis (1992).

2.1.2 Conceptual Model for DAF

Design of most DAF plants is based upon past experience and bench and pilot testing. Edzwald and co-workers (Edzwald *et al.*, 1990; Malley and Edzwald, 1991) have developed a conceptual model describing the fundamental processes involved in DAF in water treatment. The authors utilize model parameters to discuss important design and operating variables in flotation.

The model by Edzwald and co-workers considers removal of particles as a two step process: particle transport to the bubble surface and attachment of particles to

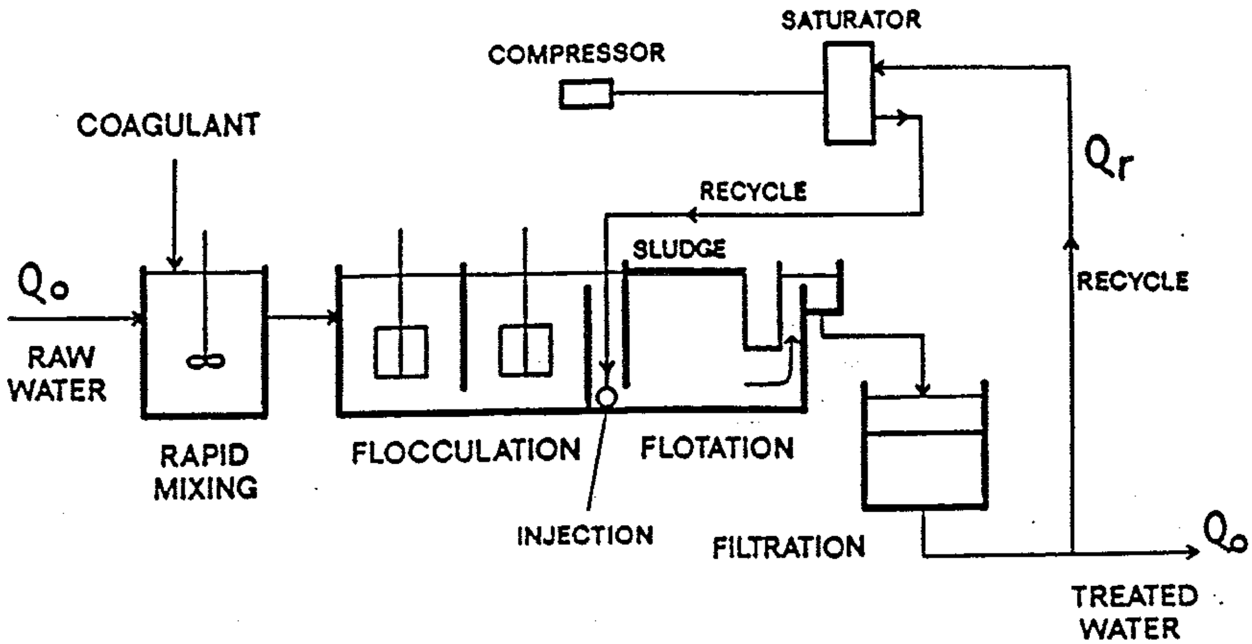


Figure 2.1 Schematic of a Typical Dissolved Air Flotation Facility (From Malley and Edzwald, 1991)

Table 2.1 Typical Design and Operational Parameters for DAF

Parameter	Range of Design Values
Chemical Pretreatment	
Coagulant Dose	determined from jar tests
Flocculation Time (min)	5-30
Mixing Intensity - G (sec^{-1})	10-150
Flotation Tank Design	
Detention Time (min)	10-20
Depth (ft)	3-11
Overflow Rate (gpm/ft^2)	$2\text{-}6^{+}$
Freeboard (ft)	0.3-1.3
Air Saturation System	
Operating Pressure (psig)	50-90
Recycle Ratio (%)	6-12
Bubble Size (μm)	10-120
Saturator Efficiency(%)	
Packed	90
Unpacked	70
Sludge	
Solids Concentration (%)	0.2-6

$^{+}$ Low values are for designs in which the filter bed is within the flotation tank.

bubbles. Considering a fixed bubble position and downward particle movement, the bubble rise velocity, U_b, can be described by the Stokes equation as:

$$U_b = \frac{g \, \rho_f \, d_b^2}{18 \, \mu} \tag{1}$$

where g is the gravitational constant of acceleration, ρ_f is the fluid density, d_b is the bubble diameter, and μ is the fluid viscosity.

Particle deposition on the bubble surface is described using the single collector collision efficiency concept with a bubble as the collector. The single collector efficiency, η is defined as:

$$\eta = \frac{\text{particle-bubble collision rate}}{\text{particle-bubble approach rate}} \tag{2}$$

Particle bubble collisions are described by three mechanisms: Brownian diffusion, η_D, interception, η_I, and gravity settling η_G. Collector efficiency by each mechanism is calculated from the following equations.

$$\eta_D = 0.9 \left[\frac{kT}{\mu\ d_p\ d_b\ U_b}\right]^{2/3} \tag{3}$$

$$\eta_I = \frac{3}{2}\left[\frac{d_p}{d_b}\right]^2 \tag{4}$$

$$\eta_G = \frac{(\rho_p - \rho_f)\ g\ d_p^2}{18\ \mu\ U_b} \tag{5}$$

where k is Boltsmann's constant (1.38×10^{-16} g cm^2 s^{-1} K^{-1}), T is absolute temperature, d_p is the particle diameter, and ρ_p is the particle density. The total single collector efficiency, η_T, equals the sum of the individual single collector efficiencies:

$$\eta_T = \eta_D + \eta_I + \eta_G \tag{6}$$

It is important to note that η_T is affected by particle size, bubble diameter, particle density and temperature. Calculations given in the papers show that parameter values typical to DAF result in a minimum η_T for particles approximately 1 μm in diameter, with increasing collector efficiency for larger and smaller particles.

An attachment efficiency parameter, α_{pb}, defined as the fraction of successful collisions, is included to give an overall single bubble removal efficiency, R as

$$R = \alpha_{pb}\ \eta_T\ (100\%) \tag{7}$$

The steady state equation for the total number concentration of particles, N_p, in terms of flotation tank depth, H, is given as

$$\frac{dN_p}{dH} = -\frac{3}{2}\frac{\alpha_{pb}\ \eta_T\ \phi_b\ N_p}{d_b} \tag{8}$$

where ϕ_b is the bubble volume concentration.

Below is a brief review of the major parameters in the model as presented in the original model (Edzwald *et al.*, 1990; Malley and Edzwald, 1991).

2.1.2.1 Attachment Efficiency (α_{pb})

The attachment efficiency, α_{pb},is the ratio of particle-bubble collisions resulting in attachment to the total number of particle-bubble collisions. Attachment efficiency is high when repulsive forces between particles and bubbles (stability) are low. Edzwald *et al.* (1990) propose two possible causes for stability between bubbles and particles: 1) repulsive electrical charge interactions between similarly charged particles and bubbles; and 2) a water layer surrounding the particles that must be displaced (hydrophilic effects). Pretreatment that destabilizes particles and increases the hydrophobic characteristics of particles is therefore important for efficient particulate removal by flotation.

2.1.2.2 Single Collector Collision Efficiency (η_T)

As defined previously, the single collector collision efficiency is related to particle size, bubble diameter, particle density and temperature. Figure 2.2 relates particle size to η for a typical DAF bubble diameter (40 μm) at two temperatures. For these conditions, the collision efficiency is at a minimum for particles approximately 1 μm in diameter. The dominant removal mechanism for particles smaller than 1 μm is diffusion. For particles larger than 1 μm the dominate removal mechanism is interception. Based upon this data, the authors suggest production of particles on the order of tens of μm and larger for effective flotation.

The model predicts minor effects on collision efficiency by typical variations in particle density and temperature. However, bubble size affects η_T with smaller bubbles providing higher collision efficiency factors. The authors point out that η_T values are an order of magnitude higher than found in water filtration because the collectors in flotation are much smaller than the collectors in filtration.

2.1.2.3 Bubble Volume Concentration (ϕ_b)

Bubble volume concentration incorporates effects of recycle ratio, saturator pressure, water temperature, and saturator efficiency in one fundamental parameter. A large ϕ_b ensures collision opportunities and lowering of floc density. Increasing saturator pressure increases air concentration in the saturated recycle stream according to Henry's Law. A higher concentration of air in a given recycle flow results in a higher bubble volume concentration. For a given air concentration (set saturator pressure), the bubble volume concentration is increased by increasing the recycle

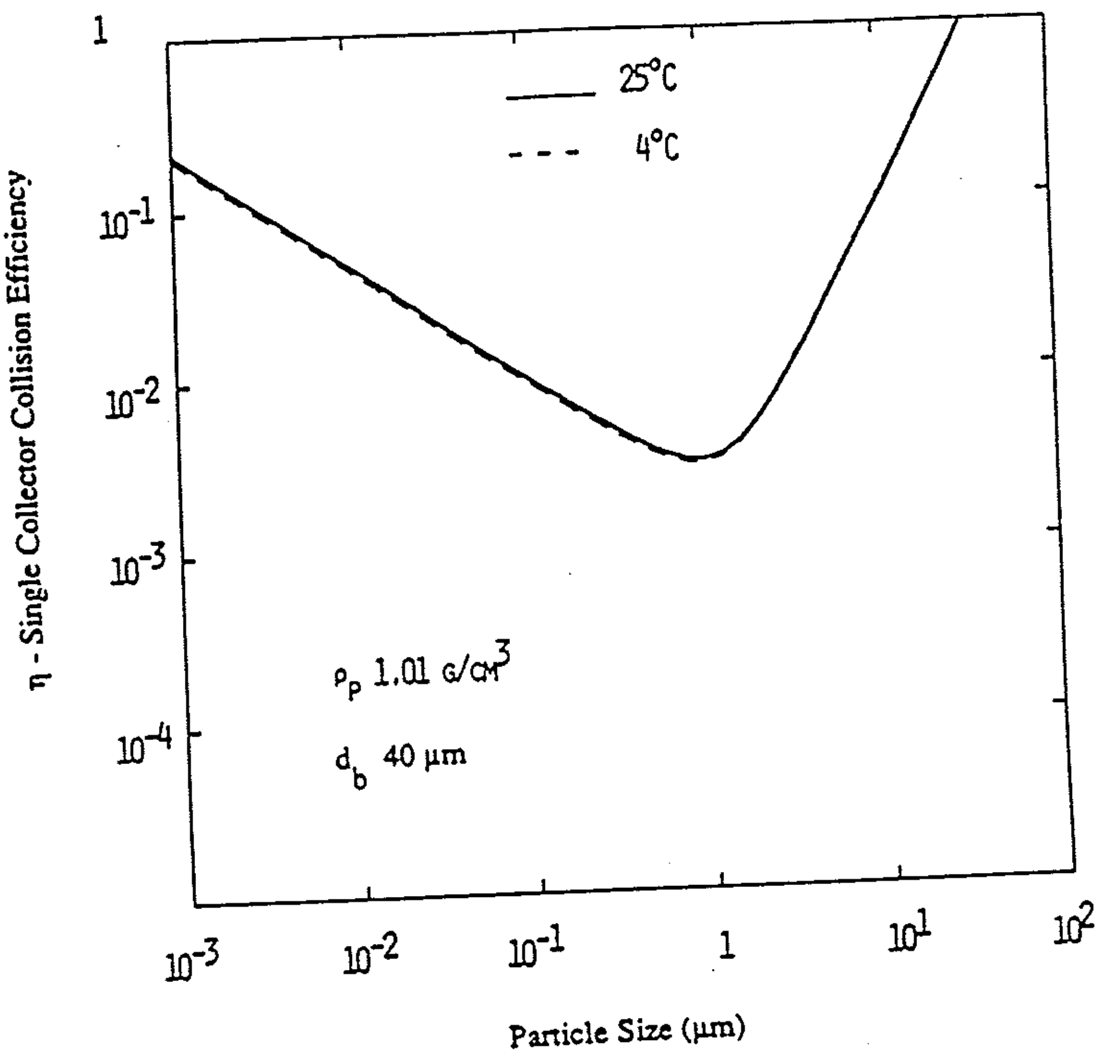


Figure 2.2 Effect of Particle Size on the Single Collector Collision Efficiency (η_T) for 4 and 25°C (From Edzwald *et al.*, 1990)

flow. In practice saturation pressure is held relatively constant while the recycle flow is changed.

2.1.3 Prior Work With DAF

Early published work on DAF in drinking water treatment was the result of a comprehensive research program sponsored by England's Water Research Centre (WRC) (Longhurst and Graham, 1987; Zabel, 1984; 1985). Janssens (1990; 1992) reported results from pilot scale studies in Belgium and Argentina. Reports on DAF in the United States began by the Lennox Institute for Research, Inc. (LIR) (Krofta and Wang, 1982; 1984; 1985). Krofta and Wang's research was based on bench and pilot scale studies in Pittsfield, Massachusetts. Olsen (1992) later reported on operational data based on full scale plants in Pittsfield.

Extensive fundamental and bench scale work on DAF has been conducted at the University of Massachusetts by Edzwald and co-workers (Edzwald, *et al.*, 1990; Edzwald and Malley, 1990; Edzwald and Wingler, 1990; Malley and Edzwald, 1991; Malley and Edzwald, 1991b; Edzwald, 1993). References to "Edzwald and co-workers" in this section relate to these papers. This work involved bench scale testing of flotation on model waters containing fulvic acid, algae, and clay suspensions. Various natural surface waters from Massachusetts were also tested.

Bench and pilot scale treatment of a surface raw water characterized by low turbidity, moderate color and periodic algae problems (Lake Whitney), was reported by Kaminski *et al.*, 1991; Walsh, 1991; Edzwald, 1993; Edzwald and Walsh, 1992; and Edzwald *et al.*, 1992. These papers will be referred to as "bench scale studies of

Lake Whitney water". Bunker (1993) evaluated DAF performance for various coagulants (including various polyaluminum chlorides, alum, and ferric chloride) on multiple raw water sources in the United States and Sweden.

A review of findings pertinent to this project is included below.

2.1.3.1 Coagulation

Multiple researchers have found that effective coagulation is required for effective flotation. Zabel (1984) gives two explanations for such a relationship: 1) destabilization of colloidal and suspended solids is required for particulate removal; and 2) coagulants allow for precipitation of organic color, such as humic and fulvic acids.

Edzwald and co-workers examined the effect of particle stability on flotation by varying pH with precipitated aluminum hydroxide at two temperatures (4 and 20 °C). Poor removal at low temperature suggested a hydrophilic effect where stabilization occurred due to the water layer between particles and bubbles. Poor removal at pH ranges corresponding to high particle charge suggested stabilization due to electrical charge interactions. These findings were supported by studies on other waters as well.

The effects of coagulation on dissolved organic matter were also studied by Edzwald and co-workers. DAF treatment was performed on synthetic water containing fulvic acid (Edzwald *et al.*, 1990) and on natural highly colored water (Malley and Edzwald, 1991). With no coagulant, flotation performance was poor. The data suggested two mechanisms of humate removal by coagulation: 1) precipitation of aluminum-humates; or 2) adsorption of humates on aluminum hydroxide flocs. Also, particle destabilization and hydrophilic effects were important. These finding were supported by studies on other waters as well.

Janssens (1990; 1992) reported that proper coagulation-destabilization was required for successful flotation based on pilot and industrial scale treatment. Also, flotation "collectors", (described as: "usually a surface active material [which] adsorbs to the solid surface") which increased the hydrophobic nature of particles, improved treatment by DAF.

2.1.3.2 Flocculation

In general, researchers have found some degree of flocculation is necessary for effective flotation. However, there is some disagreement on the most effective flocculation time and therefore the optimum particle size for flotation. Zabel (1984; 1985) concluded that 12 minutes of flocculation time is required for flotation of algal laden waters and 20 minutes is required for treatment of soft, highly colored water. Zabel also reports effective treatment by flocculation at Gt values between 40,000 and 60,000 and optimum treatment at a G value of 10 s^{-1}.

Edzwald and co-workers suggest creation of pin-point floc's (tens of microns in diameter) for effective flotation based on the previously discussed conceptual model and experimental results. The flocculation period to create such flocs depends on raw water but in general is approximately 5 minutes. For most of the test conditions reported no additional significant benefits were reported for flocculation times greater than 5 minutes. Experiments involving some waters treated with alum at 20°C and with polyaluminum chloride (PACl) at 4 and 20°C, showed no effect of flocculation time on flotation performance.

Pilot scale treatment of Lake Whitney raw water found adequate treatment at both 8 and 16 minutes of flocculation time and poor treatment with no flocculation. Particle analyses showed few differences in the average particle size after flocculation for the two flocculation conditions studied. Particles remaining after flotation were primarily smaller than 10 μm in diameter.

Janssens (1990; 1992) suggests the creation of light and small but strong flocs with a high density for effective flotation. Such flocs rise easily in the flotation chamber and resist the relatively heavy turbulence and shear created by injection of the recycle flow. Short flocculation times of 5-6 minutes with G values of 30-80 s^{-1} were reported to produce good results. Also, tapered flocculation was not found to be necessary.

Bunker (1993) found that flocculation times as low as 5 minutes were adequate for treating several raw waters in the United States and Sweden. This was true for treatment using several PACs and ferric chloride at all temperatures and alum at 20°C. Treatment involving alum at 4°C required a minimum of 10 minutes flocculation time.

2.1.3.3 Air requirements

Zabel (1984; 1985) and Longhurst and Graham (1987) found that flotation efficiency depended on the total quantity of air produced and not the saturator pressure or recycle value individually. For most surface water they concluded that the optimum quantity of air depended only on the amount of water treated. One exception was treatment of waters high in suspended solids concentration, which required a higher quantity of air. However, no specific data for treatment at low air concentrations (i.e. low recycle ratio) were reported. The optimum quantity of air was reported as 7-8 g of air/m^3 of raw water, which corresponds to saturator pressures between 50-60 psig and recycle ratios between 7 and 8 percent. Recycle ratios between 6 and 10 percent were recommended. Low recycle flows can result in inadequate mixing between flocculated water and the recycle flow; high recycle flows can result in floc break-up due to turbulence.

Edzwald and co-workers concluded that flotation performance depended on the total concentration of air and not recycle or saturator pressure. The two parameters were incorporated into the bubble volume concentration, which was described previously. Edzwald and co-workers found that the optimum bubble volume concentration depended on raw water quality. For waters containing clay, a bubble concentration of 4,600 ppm (8% recycle, 70 psig, 70% saturator efficiency, 20°C) produced effective flotation. For waters containing humic substances or algae with no clay, bubble concentrations of 2,900 ppm (5% recycle, 70 psig, 70% saturator efficiency, 20°C) and lower achieved good results.

Pilot scale treatment of Lake Whitney water by DAF found excellent DAF performance at recycle ratios of 5 percent or more (saturator pressure of 74 psig) during three different times in the year. On the last testing, after a new eductor was installed, a recycle ratio of 4 percent achieved good results. At low recycle ratios the authors reported eductor failure due to insufficient headloss across the eductor.

2.1.3.4 Sludge Removal

Most information on sludge removal was based on operational experiences at existing DAF plants as reported by Zabel (1984; 1985) and Longhurst and Graham

(1987). The two main types of sludge removal devices in use are mechanical scraping and flooding. Flooding involves intermittent raising of the water level in the DAF unit until the sludge layer flows off the tank into a trough. This process is reported to have little effect on treated water quality but creates sludge with a high water content. Mechanical scraping involves either intermittently or continuously scraping sludge from the surface of the tank to a 'beach' at one end of the tank. Full and partial length scrapers are commonly used while beach scrapers (that only scrape above the sludge beach) are less common.

Full length scrapers create a sludge of high solids concentration but require attention to avoid water quality deterioration. When the scraper speed is too slow or if the sludge is not scraped frequently, the sludge layer will become thick. When the sludge layer is thick, operation of the scrapers can result in sludge breakup and disturbance of the layer resulting in deterioration of water quality.

Few reports were found on the stability of the sludge layer during normal operation when sludge removal equipment is not operating. Zabel (1984; 1985) reported sludge breakup and water deterioration (with no mechanical removal) after 30 minutes of accumulation at plants treating soft, highly colored waters. Sludge produced from turbid river water or stored algae laden water was reported to be stable after 24 hours of accumulation.

2.2 Ozone as an Oxidant

Ozone use for water disinfection began in the 1880s in Europe and increased until World War I when inexpensive chlorine became readily available. After World

War II, ozone use again grew, primarily in Europe and somewhat in North America. In the United States the 1986 Amendments to the Safe Drinking Water Act, which have lead to EPA's Surface Water Treatment Rule and the newly proposed Disinfection/Disinfection by-Products (D/DBP) rule, are increasing interest in the use of ozonation in drinking water treatment. In Europe, the EEC regulations on drinking water quality are causing an increase in ozone use (Langlais *et al.*, 1991).

Langlais *et al.* (1991) reported the following uses of ozonation in drinking water treatment: 1) disinfection and algae control; 2) oxidation of inorganic pollutants, particularly iron and manganese; 3) oxidation of organic micropollutants, including taste and odor compounds, phenolic pollutants, and pesticides; 4) oxidation of organic macropollutants, including bleaching of color, increasing biodegradability of organics, destruction of trihalomethane formation potential (THMFP) and total organic halide formation potential (TOXFP) and chlorine demand and; 5) improvement of coagulation.

The SCCRWA has been studying ozonation as a disinfectant at the West River Treatment Plant pilot facility since 1989 to decrease formation of chlorinated DBPs and to eliminate objectionable taste and odors. Work since 1991 has focused on the use of biologically active filtration following ozonation and a comparison of the use of pre-ozonation and GAC/sand filters versus ozonation and GAC following conventional dual media filtration. Section 2.4 contains detailed discussions of previous work at West River.

2.2.1 Fundamental Aspects of Oxidation by Ozone

Ozone reacts with various compounds in two ways: 1) by direct reaction with molecular ozone; and 2) by indirect reaction with the radical species that are formed when ozone decomposes in water. The direct molecular ozone reactions are extremely selective and are limited to unsaturated aromatic and aliphatic compounds and specific functional groups. In the presence of certain initiators ozone decomposes to form highly reactive hydroxyl (OH^0) radicals. (Langlais *et al.*, 1991).

The decomposition pathway of ozone is shown in Figure 2.3. Ozone reacts with an initiator, here the hydroxyl ion (OH^-), to form the superoxide ion (O_2^-). Initiators capable of inducing this reaction are: 1) inorganic compounds including hydroxyl ions, hydroperoxide ions (HO_2^-) and some cations; 2) organic compounds including glyoxylic acid, formic acid and humic substances; and 3) UV light at 253.7 nm. The superoxide ion reacts with additional ozone to eventually form hydroxyl radicals (OH^0). Hydroxyl radicals are highly reactive oxidants that are less specific than molecular ozone with reactions involving substrate compounds. If the hydroxyl radical is not consumed it reacts further with molecular ozone completing the circle. Compounds that consume hydroxyl radicals and therefore impede completion of the cycle are inhibitors. Examples of inhibitors are bicarbonate and carbonate ions, alkyl groups, tertiary alcohols, and humic substances. (Langlais *et al.*, 1991)

2.2.2 Effects of Ozone on Coagulation/Solid Separation

No references on ozonation prior to DAF were found in the literature. Langlais *et al.* (1991) reported construction of three ozoflotation plants in France. A

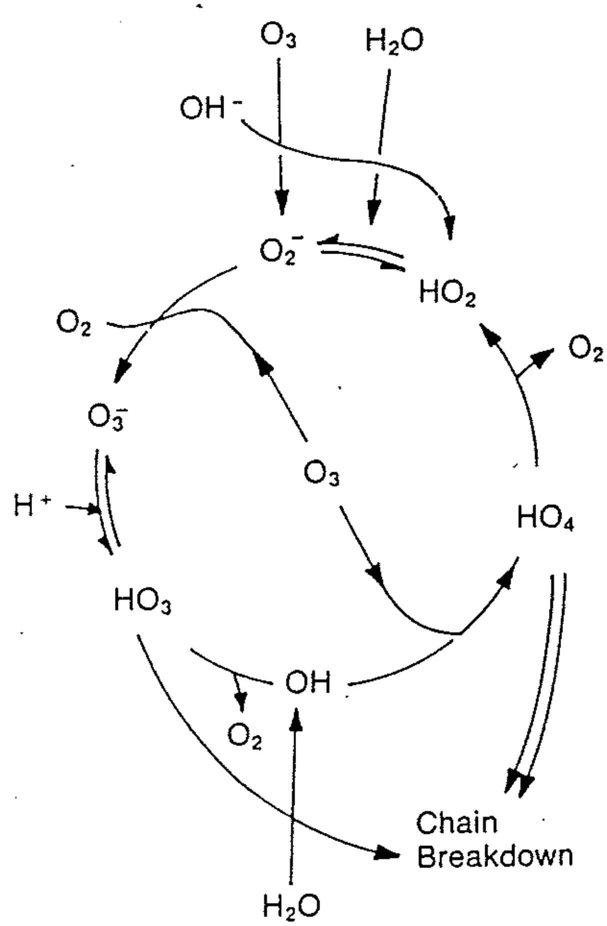


Figure 2.3 **Reaction Diagram for Ozone Decomposition Process (From Langlais *et al.*, 1991)**

typical ozoflotation plant is shown in Figure 2.4. The porous diffusers (C) create a maximum quantity of fine bubbles of ozonized gas with an additional water stream. Larger bubbles rise through the ozonation compartment (A) and fine bubbles (diameter between 200 and 500 μm) are entrained into the flotation compartment (B). The process was presented as a method to control algae. Langlais *et al.* (1991) suggest a negative effect of preozonation on DAF when describing ozoflotation: "[the] process represents a compromise between conventional preozonation, which results in inefficient flotation . . ." but no explanation is provided.

The effects of ozone on coagulation are considered secondary effects (effects that do not occur instantly at the moment of ozone reaction). Langlais *et al.* (1991) report the following possible effects of pre-ozonation: 1) shift in particle size distribution towards larger sizes; 2) the formation of colloidal particles from dissolved organic matter; 3) improved removal of TOC or turbidity by settling, flotation or filtration; 4) an increase in floc settling velocities; 5) extended filter run length due to slower head loss buildup or delayed breakthrough.

For conventional treatment, Langlais *et al.* (1991) reported that pre-ozonation can facilitate the removal of readily coagulatable material, resulting in lower required coagulant dose and improved sludge characteristics, but does not affect particulate removal by subsequent filtration. For direct filtration, pre-ozonation may encourage the removal of particles that could not otherwise be removed, regardless of coagulant dose.

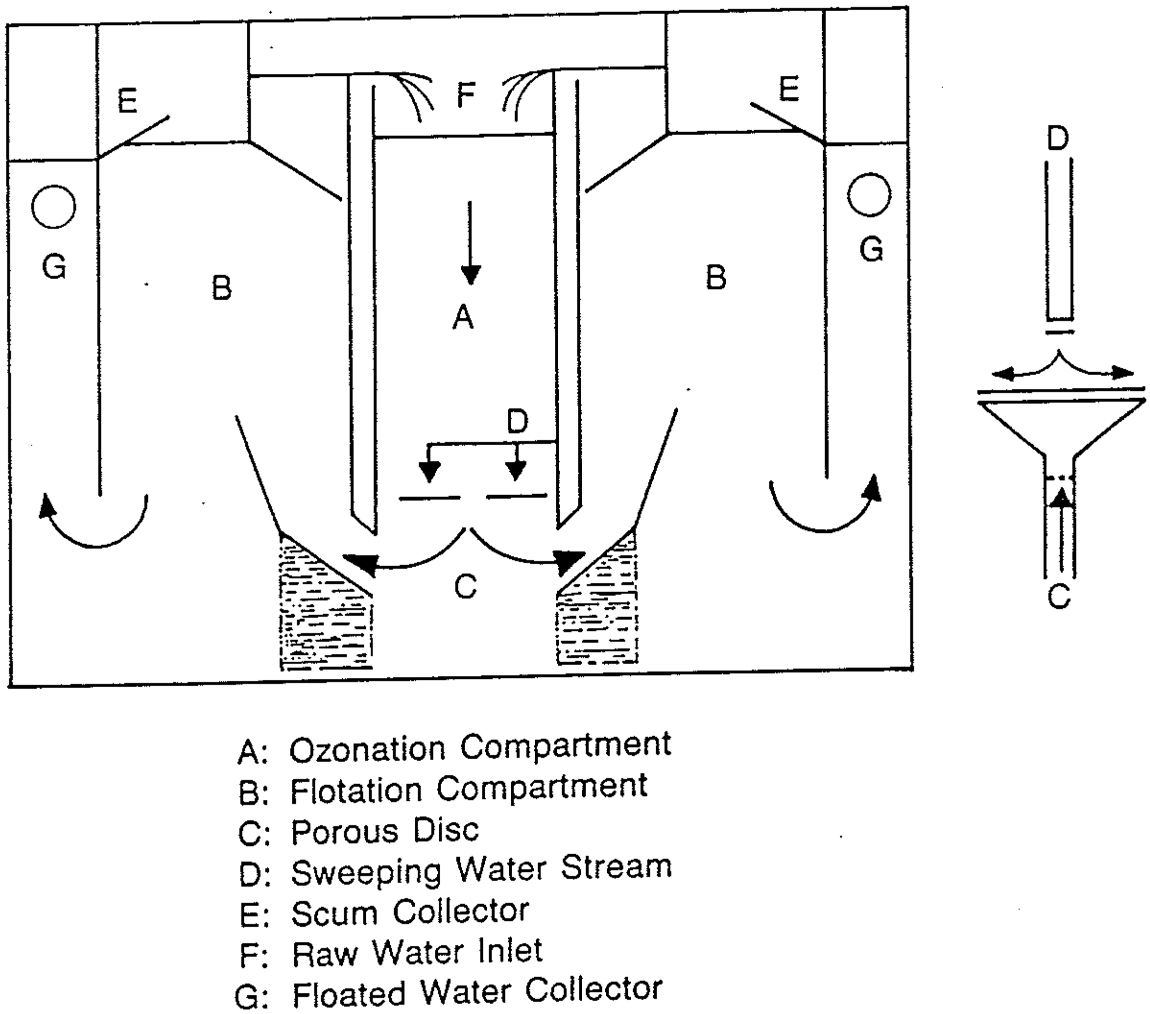


Figure 2.4 Schematic of an Ozoflotation Unit (From Langlais *et al.*, 1991)

2.3 Direct Filtration

Direct filtration treatment of drinking water involves coagulant addition, rapid mix, flocculation and rapid filtration. Contact or in-line direct filtration is a similar process where the flocculation step is omitted. Culp (1977) reports use of direct filtration during the early 1900's but the process was ineffective because of rapid head loss development in the fine- to course single media beds. Development of dual and mixed media filter beds during the 1960's and 1970's and increasing regulation of drinking water treatment increased interest in direct filtration.

The main advantage of direct filtration is savings in capital and operating costs. Compared to conventional treatment, capital cost savings can amount to 30 percent and chemical cost savings can be 10-30 percent compared to conventional treatment (Culp 1977). Savings in capital costs result from elimination of sludge-collecting equipment, settling basin structures, flocculation equipment, and flocculation basin structures. Savings in chemical costs result from lower coagulant dosages required to produce filterable water compared to settlable water.

Culp (1977) reported the following disadvantages to direct filtration: 1) filter runs generally shorter than conventional treatment; 2) higher water wastage (6 percent compared to 2 percent for conventional treatment) due to more frequent filter backwashing; and 3) a need for increased operator vigilance due to shorter times between coagulant addition and filtration.

Several researchers have proposed criteria for direct filtration based on raw water characteristics. Culp (1977) recommended direct filtration for waters having low color and turbidity less than 100-200 ntu, low turbidity and color below 100 units, or both color and turbidity below 25. McCormick and King (1982) recommended direct filtration for surface waters with turbidity less than or equal to 25 ntu and low color and algal concentrations. Edzwald *et al.* (1987) suggested direct filtration for waters of low turbidity and TOC of 5 mg/L or less. Pilot studies are recommended to determine direct filtration treatment performance on a given source water.

2.4 Previous Pilot Experience at the WRTP

Pilot plant work has been conducted by UMass and the SCCRWA at West River since 1989. Early work focused on alternative oxidation processes (AOPs) on the direct filtration process. Schneider (1990) utilized ozone as a pre-oxidant; Fox (1990) focused on peroxone (hydrogen peroxide addition before ozonation) as a pre-oxidant; and Vinod (1992) continued work on ozone and peroxone oxidation while evaluating manganese oxidation and removal. The studies in 1989 and 1990 were conducted with intermittent operation of the pilot plant using anthracite/sand filters (the same as used in the full scale plant) (Tobiason *et al.*, 1992). The pilot plant was operated continuously in 1991 with GAC/sand filters in parallel with anthracite sand filters. The 1991 work focused on a parallel comparison of pre-ozonation versus no ozonation and the effects of GAC/sand filters versus anthracite/sand filters (Tobiason *et al.*, 1993a).

Schneider (1990), found that ozonation increased filter run time by 4.5-6 hours and consistently improved effluent turbidity. Particle data showed ozonation shifted the particle size distribution toward larger particles; after coagulation and flocculation, the ozonated water tended to have fewer particles. Ozonation reduced the measured levels of UV254 and improved overall removal (through filtration) of UV254. Ozonation of raw water increased the measured DOC and inhibited DOC removal through treatment. Two explanations were given for the increase in DOC: 1) a reduction in molecular weight of the NOM causing a decrease in adsorption of organics onto inorganic particles; or 2) dissolution of particulate carbon. Ozone decreased THMFP of the raw water and resulted in slightly reduced THMFP levels in the filter effluent compared to no ozonation.

Fox (1990) found that peroxone oxidation provided fewer benefits for treatment than ozone oxidation as measured by overall removal of turbidity, measured particles, and THMFP. The choice of oxidants had little effect on filter run time, UV254 and DOC levels, and the removal of different molecular weight fractions of NOM.

Vinod (1992) found that the use of ozone resulted in a higher reduction of UV254 compared to no pre-oxidant and did not affect DOC removal across the filters. Pre-ozonation resulted in decreased filtered particle counts with no shift in the PSD after pre-oxidation. Pre-oxidation by peroxone resulted in similar filtered water quality as measured by DOC, UV254, turbidity, particle counts and rate of headloss development. Manganese data showed the pilot plants (with ozone or perozone application) removed less manganese than the full scale plant (with potassium permanganate application). Variable ozone dose experiments showed that ozone at 1 to 2 mg/L oxidized soluble manganese to colloidal manganese oxide to a certain extent.

Based on 1991 data and previous work, Tobiason *et al.* (1993a) concluded that pre-ozonation does not have a large impact on in-line direct filtration at West River. During 1991, the effects of GAC/sand filtration depended on the parameter measured. The GAC/sand filters had significantly longer run times than the full-scale plant but the effects of ozone were reported as: 'not always significant'. Turbidity for both the GAC/sand and anthracite/sand filters and both the pre-ozone and no ozone trains were similar. Dissolved organic carbon levels for the GAC/sand filtered water were found to be consistently lower than for the anthracite/sand filtered waters and the effects of pre-ozonation were small. GAC/sand filters backwashed with chlorinated water were found to produce slightly higher levels of DOC. UV254 data was similar to DOC values except a reduction in UV254 was observed following ozonation where it was not for DOC. The authors suggested biological activation of the GAC/sand filters improved DOC removal for the GAC/sand filters versus the anthracite/sand filters.

CHAPTER III

3. EXPERIMENTAL METHODS AND MATERIALS

This chapter contains descriptions of experimental methods and materials used throughout this report. Descriptions of the West River Treatment Plant (WRTP), the dissolved air flotation (DAF) pilot train and the direct filtration (DF) pilot train are included. Descriptions of bench scale DAF experiments, routine monitoring of the pilot plants and pilot scale experiments on the DAF pilot train are provided. Finally, analytical methods and procedures are described.

3.1 Descriptions of the WRTP and the Pilot Plants

The pilot work reported took place at the existing WRTP located outside New Haven, Connecticut. Work was conducted on two pilot treatment trains located inside the WRTP.

3.1.1 The WRTP

The WRTP is a 10.4 mgd in-line direct filtration (no flocculation and sedimentation) treatment plant. Raw water for the WRTP is drawn from Lakes Glen, Watrous and Dawson, three impoundments of the West River. Primary removals are from Lakes Glen and Watrous while Lake Dawson, which has occasional algal problems, is normally only used during periods of high demand. The relatively high quality water is typical of New England surface supplies with low turbidity and color.

A schematic of the WRTP is provided in Figure 3.1. Potassium permanganate ($KMnO_4$) and caustic soda (NaOH) are added to a three bay under-over baffled contact tank. Potassium permanganate is added as a pre-oxidant primarily for manganese control. Primary coagulants are added in a four bay under-over baffled rapid mix tank. Ferric Chloride and a cationic polymer, Floxan 5062 (Diamond Shamrock) were used as primary coagulants during this study.

Filtration is provided by dual media rapid filters that consist of 20 inches of anthracite over 10 inches of silica sand. Filters at the WRTP are normally operated at hydraulic filter loading rates of 3 gpm/ft^2 during the summer and 1.5-2.0 gpm/ft^2 during the winter. Disinfection is provided by addition of chlorine prior to two parallel three million gallon clearwells. Hydrofluorosilicic acid is added prior to the clearwell for fluoride addition. Zinc polyphosphate for corrosion control and caustic for pH control are added after the clearwells.

Typical coagulant dosages at the WRTP during the period of study (February 1992 to December 1992) were 6.0-8.5 mg/L $FeCl_3$ and 2.0-2.6 mg/L polymer (as product). Other typical doses during the same period were 0.3-0.5 mg/L of $KMnO_4$, 1.6-2.4 mg/L of chlorine, 0.9-1.0 mg/L of hydrofluorosilicic acid and 1.9-2.1 mg/L of zinc polyphosphate (as phosphate).

3.1.2 The DAF Pilot Plant

A schematic of the DAF pilot plant is provided in Figure 3.2. Primary coagulants are added prior to an in line static mixer. The two primary coagulants used during the study were $FeCl_3$ and the cationic polymer used at the full scale plant.

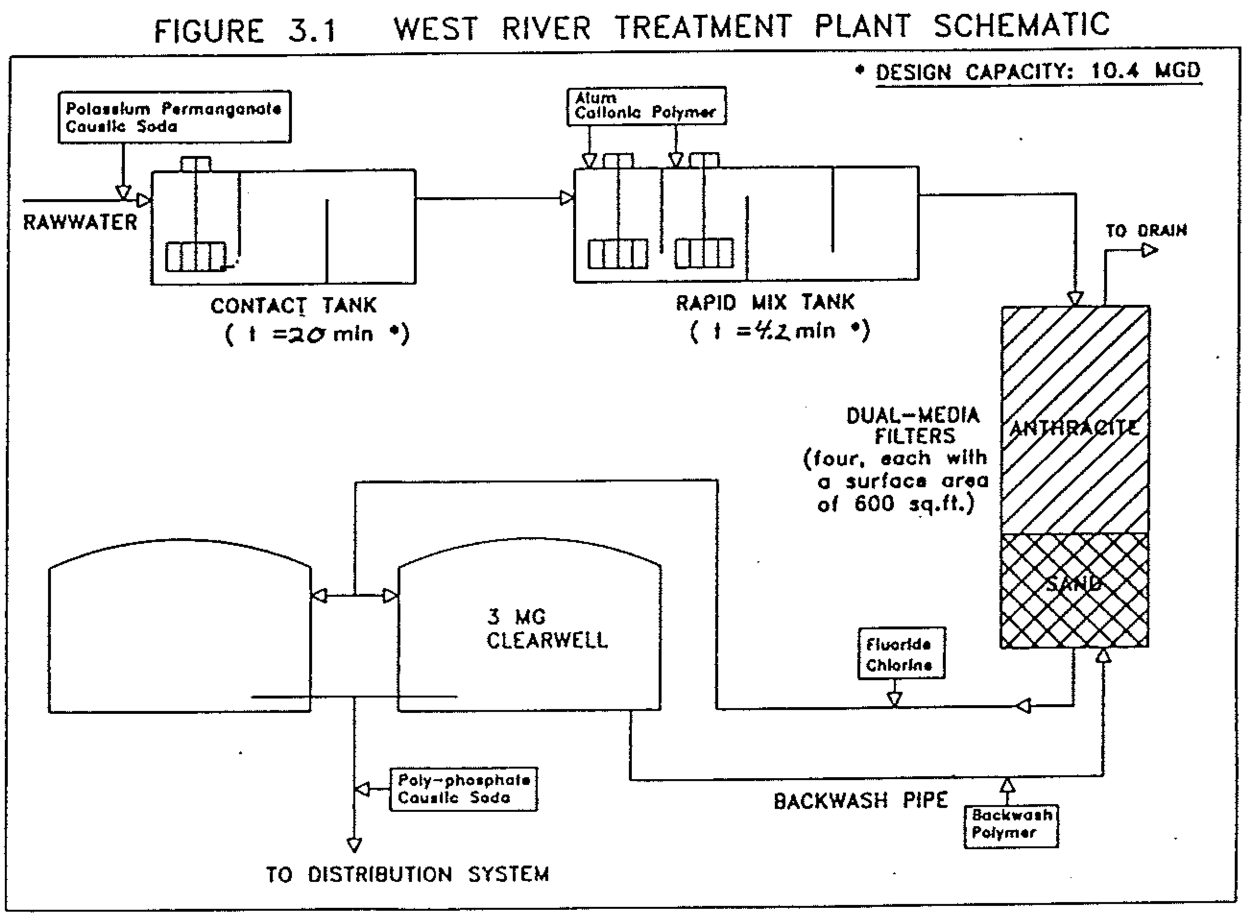
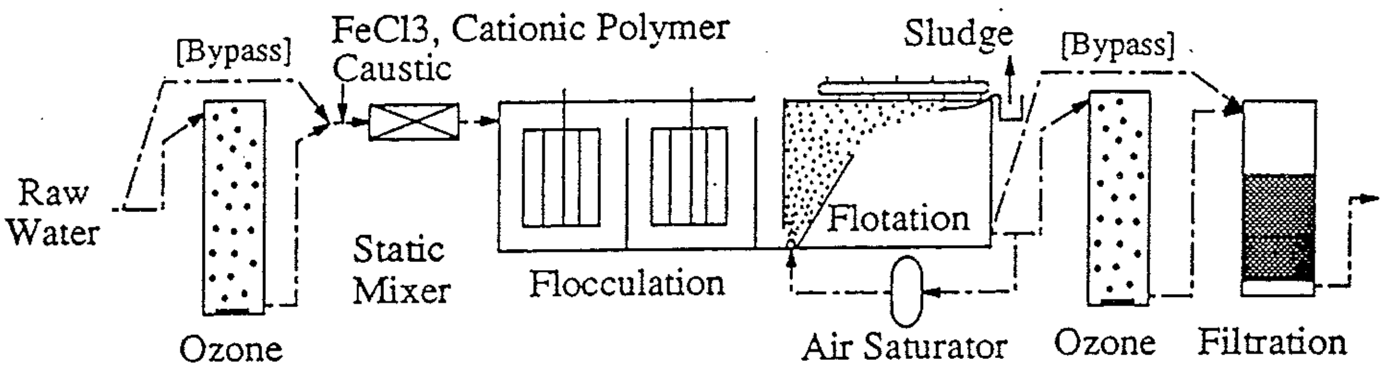


Figure 3.1 Schematic of the WRTP (From Vinod, 1992)



Train #3: Dissolved Air Flotation

Figure 3.2 Schematic of the DAF Pilot Plant

Under normal operating conditions coagulant dosages were the same as used at the full scale plant. Coagulant dosages were determined from the drawdown of chemical feed tanks each day.

After static mixing, the water enters two flocculation bays in series, each with an 8 minute detention time at a flow of 45 gpm. The flocculation bays were configured such that the first flocculation bay could be by-passed resulting in 8 minutes of total detention time. Mixing is provided in the flocculation bays by variable speed vertical slotted paddles.

Flocculated water flows directly into the bottom of the flotation tank. As water flows past the recycle injection header, destabilized particles attach to bubbles produced by the recycle line injection header. The particle-bubble agglomerates float to the surface where they are periodically removed by a full length mechanical scraper with rubber blades. Recycle flow is taken from the DAF effluent (clarified water) for air saturation.

The air saturation system consists of an air saturation vessel, which is half filled with air and half filled with water at steady state. Recycle water is educted with air from the air/water saturation vessel and sent to the bottom half of the air saturation vessel. Air is pumped to the top half of the saturation vessel from an oil-free compressor operating at 70 to 80 psig. The supersatured water in the air/water saturation vessel is injected into the bottom of the DAF unit through a dispersion header containing two injection nozzles.

Clarified water is sent to dual media rapid filters that consist of 20 inches of Calgon Filtrasorb granular activated carbon (GAC) (8x20) media over 10 inches of silica sand. Sieve analysis by the SCCRWA in September of 1991 resulted in measurements of an effective GAC media size with 10 percent smaller by weight (d_{10}) of 1.07 mm, an effective media size with 60 percent smaller by weight (d_{60}) of 1.64 mm and a uniformity coefficient (UC) of 1.53. The filter media is contained in a 11.6 feet tall cylindrical column with an inside diameter of 12 inches. Filter backwash water is supplied by stored pilot filtered water. Headloss development was measured across the filters at 5 and 10 inches into the GAC layer, at the GAC/sand interface, 5 inches into the sand layer and across the entire filter. Pressure manometers consist of mercury filled U-tubes with one end connected to the sample tap and the reference end connected above the top of the filter media. Measurements in inches of mercury are converted to inches or feet of water.

The DAF pilot plant was configured such that ozone could be applied either prior to coagulant addition (pre-ozonation) or after flotation (intermediate ozonation). The ozonation system consists of an ozone generator (Griffin Technics Inc., Model - 1B), an ozone monitor (PCI Model EG 2001) and two counter current ozone contactors. Ozone is generated from compressed, dehumidified air by formation of an electric arc. The air/ozone mixture is pumped to porous stone diffusers at the bottom of the ozone contactors.

In the pre-ozonation configuration, raw water is pumped to two ozone contactors in parallel. With flows of 27 gpm and 22 gpm to each contactor, the detention time for each contactor is 5 minutes. Gas flow from the ozone generator is split appropriately between the two contactors. In the intermediate-ozonation configuration, clarified water is pumped to one ozone contactor. At a flow of 12 gpm, the detention time is 10 minutes.

3.1.3 The DF Pilot Plant

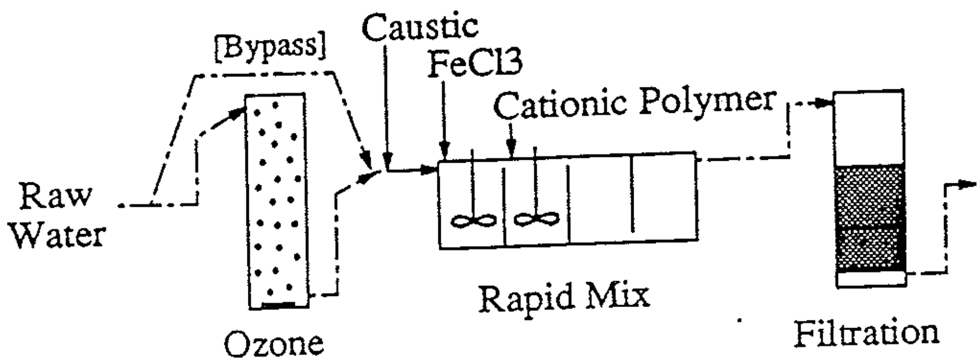
A schematic of the DF pilot plant is provided in Figure 3.3. Ozonation of raw water (pre-ozonation) occurred throughout the study for the DF pilot train. The flow of 5.5 gpm through the ozone contactor results in a detention time of 10 minutes. Primary coagulants are added to the rapid mix tank (detention time of 5 minutes). The rapid mix tank consisted of four bays in series with rapid mix provided in the first two bays. $FeCl_3$ was added to the first bay and cationic polymer was added to the second. Coagulant dosages were the same as the dosages used in the full scale plant. Destabilized water was sent to a dual media GAC/sand filter identical to the filter used in the DAF train.

3.2 Pilot and Bench Scale Experiments and Sampling

3.2.1 Bench Scale Experiments

Bench scale DAF experiments were carried out at UMass to determine the coagulant dose for treatment of West River source water by DAF utilizing ferric chloride only. The range of successful $FeCl_3$ dosages on the bench scale were then evaluated at the pilot scale during run #3.

The bench scale DAF system (Aztec Environmental Control, Ltd., U.K.) consists of an unpacked saturator, four 1.4 liter Plexiglass jars, four retractable flocculation paddles and nozzles for each jar to allow injection of the air saturated



Train #2: In-Line Direct Filtration

Figure 3.3 Schematic of the DF Pilot Plant

water. All four flocculation paddles have a single speed control. The system allows for rapid mixing, flocculation and flotation in the same jar. A sample port is located at the base of each jar for flocculation and flotation sampling.

For each experiment, each flotation jar was filled with 1 liter of raw water. Coagulant was added at the appropriate concentration and the pH was adjusted to 6.7 $\pm$ 0.2 with caustic (NaOH) or hydrochloric acid (HCl). Rapid mixing was performed for 10 seconds at 400 rpm ($G=380\ sec^{-1}$) followed by flocculation for 16 minutes at 100 rpm ($G=55\ sec^{-1}$). Flocculation samples were taken for measurement of turbidity. After flocculation, air saturated flow from the saturator was injected into the flotation jars. For this research, the saturator pressure was held constant at 70 psig and the recycle volume was 8 percent. Samples were taken after 10 minutes for measurements of turbidity, UV254, and pH.

3.2.2 Pilot Plant Daily and Routine Sampling

The three pilot trains were sampled on a daily basis by SCCRWA personnel. Turbidity, UV254, and pH were measured after filtration on both the DAF and DF pilot trains, and after flotation on the DAF train. Headloss development was measured on all filters on a continuous, automated basis. Filters automatically backwashed at eight feet of total headloss.

The pilot plants were sampled across treatment several times throughout 1992 by UMass personnel. Turbidity, UV254, pH, and particle counts were measured on site. Samples for dissolved organic carbon (DOC), assimilable organic carbon (AOC), total trihalomethane formation potential (TTHMFP) and haloacetic acid formation potential (HAA5FP) were collected, stored and returned to UMass for analysis. Analytical methods are presented in Section 3.3. Sample locations included raw water, after ozonation (either pre-ozonation or intermediate ozonation) on both trains, rapid mix on the DF train, flocculation on the DAF train, after flotation on the DAF train and after filtration on both trains and the WRTP. Results from routine sampling of turbidity, UV254, and DOC measurements across treatment are presented in Section 4.2.

3.2.3 DAF Pilot Plant Experiments

Twenty pilot plant 'runs' were performed on the DAF train to evaluate process parameters. To evaluate recycle ratio, DAF loading rate, sludge removal rate, GAC versus anthracite filters, and the effects of pre-ozonation, the parameter of interest was varied during the run. To evaluate coagulant types, effects of intermediate-ozonation, filter loading rate, and flocculation time, the parameter of interest was changed between runs. Runs started with backwash of the filter and continued for a pre-determined length of time unless the filter automatically backwashed at eight feet of total headloss, or finished water quality was poor (i.e., turbidity greater than 0.15 ntu or UV254 removal less than 50 percent). If a process variable was changed during the run, each condition was allowed to run for at least four hours. If the process variable was changed between runs, the run was continued for at least 11 hours.

Typically, filtered water turbidity and UV254 and filter headloss development were measured once every thirty minutes during a run. For selected runs, the DAF effluent (after DAF) turbidity was also measured every thirty minutes. Turbidity, UV254 and pH were measured across treatment three to six times per run. Also particle counts and DOC were measured across treatment one to four times during each run.

For selected runs, DAF performance was compared to the parallel direct filtration train for direct comparisons between the DF and DAF/filtration processes and to evaluate changes in coagulation conditions and raw water quality during and between runs. Measurements on the DF train were similar to measurements on the DAF train.

3.3 Analytical Methods and Procedures

Turbidity, UV254, pH and particle analyses were performed at the WRTP. The instruments at West River were maintained and calibrated by SCCRWA personnel. Turbidity was measured using a Hach ratio turbidimeter (Model 18900). The instrument was calibrated using formazine standards and the calibration was checked every day using secondary polymer standards. The pH was measured using a Corning pH meter and probe (Model 140) that was calibrated every morning. UV254 measurements were performed on a Milton Roy Spectronics 1001 spectrophotometer with a quartz cell with a 1 cm path length. The spectrophotometer was zeroed using distilled water filtered with a 0.20 micron filter. UV254 samples were filtered through a GF/C Glass Microfibre filter with an effective pore size of 1.2 μm. The GF/C filters were prewashed with distilled water prior to sample filtration.

Samples for DOC analysis were filtered using the same procedure and filters used to prepare the UV254 samples. DOC samples were stored in 40 mL glass vials with teflon caps and refrigerated at the WRTP until transport to UMass. The storage vials were acid washed (20% sulfuric acid for 4 hours) and baked at 60°C for 4 hours. Upon arrival at UMass, the DOC samples were acidified with concentrated nitric acid to a pH of 1-3 and refrigerated at 4°C until further analysis.

DOC analysis was performed using a Dohrmann DC-80 total organic carbon analyzer (Rosemount Analytical Corp). Organic carbon is measured by the ultraviolet promoted persulfate oxidation of organic carbon to carbon dioxide. The carbon dioxide level is then measured by infrared detection. Samples are sparged with nitrogen at low pH to remove inorganic carbon.

Standards of 10 and 3 mg/L of carbon are prepared from a potassium hydrogen phthalate (KHP) primary standard of 2000 mg/L as carbon. The 2000 mg/L standard is prepared by dissolving 4.25 grams of reagent grade potassium hydrogen phthalate ($C_8H_5O_4K$), KHP, and 1 ml of concentrated nitric acid in 1000 milliliters of super-Q water (tap water treated with reverse osmosis, ion exchange, carbon adsorption and 0.2 μm filtration). The instrument is calibrated using an average of three injections of the 10 mg/L standard and is checked using the 3 mg/L standard. Measurement of organic carbon in the DOC samples are then measured two times for each sample and averaged. The persulfate solution is prepared by dissolving 20 grams of reagent grade potassium persulfate and 1 mL of phosphoric acid in 1000 milliliters of super-Q water.

Particle analyses were performed using a Hiac/Royco particle analyzer (Model 4300) in conjunction with a Model ABS sampler and a Model No. HR-120 light blockage sensor. The light blockage sensor detects the particles and the particle analyzer sorts and counts the signals generated by the sensor. The particle analyzer has 15 channels that cover a particle range of 2 μm to 120 μm diameter, and one channel for particles greater than 120 μm. The channel widths on the analyzer were normalized such that all particle channels had equal logarithmic widths. Samples were measured at a flow rate of 20 ml in 30 second (40 ml/min). The coincidence limit of the sensor is 6000 total counts/ml. Samples with total counts above the coincidence limit of the sensor were run using pilot or full scale filtered water of measured particle number for dilution. Particle counts of one sample were measured three times and reported as an average of the three measurements.

Throughout this report particle data are presented as total particles per milliliter for 2 μm to 92 μm average diameter particles, number average diameter of particles ($\bar{d}_N$) defined as

$$\bar{d}_N = \frac{\sum_i N_i \, d_{pi}}{\sum_i N_i} \tag{9}$$

and volume average diameter of particles ($\bar{d}_V$) defined as

$$\bar{d}_V = \left[\frac{\sum_i N_i \, d_{pi}^3}{\sum_i N_i} \right]^{1/3} \tag{10}$$

where N_i is the number of particles in the ith size range and d_{pi} is the average particle diameter in the ith size range.

For the experiments evaluating flocculation conditions prior to flotation, the particle size distributions of the particle data are presented as plots of the number distribution function (NDF) versus the log of the particle diameter, where NDF_i is defined as

$$NDF_i = \frac{dN_i}{d(\log(d_{pi}))} \tag{11}$$

and the volume distribution function (VDF) versus the log of the particle diameter where VDF_i is defined as

$$VDF_i = \frac{dV_i}{d(\log(d_{pi}))} = \frac{\pi \, d_{pi}^3 \; dN_i}{6 \, d(\log(d_{pi}))} \tag{12}$$

and V_i is the average volume of a particle in the ith size range.

CHAPTER IV

4. RESULTS AND DISCUSSION

This chapter contains results from the pilot run experiments, bench scale DAF experiments, and routine monitoring of the pilot plants. Results and discussion are presented for the effects of process parameters on DAF performance, and for general treatment performance of the DAF pilot train with comparisons to the DF pilot train and the WRTP.

4.1 Effects of Process Parameters on DAF Performance

A list of the pilot run experiments performed during 1992 is found in Table 4.1. Results from these experiments and the DAF bench scale experiments are presented herein. The effects of coagulation, DAF recycle ratio, sludge removal, flocculation time prior to flotation, and ozonation on flotation and filtration are discussed. Throughout this section polymer doses are reported as mg/L of product. The Floxan 5062 used at West River is approximately 50 percent polymer and 50 percent water.

4.1.1 Effects of Coagulation

Edzwald *et al.* (1987) reported effective treatment in direct filtration with coagulation by alum alone and by cationic polymer alone, although alum coagulation resulted in increased removal of TOC and TTHMFP. However, coagulation by alum in direct filtration produces aluminum hydroxide that can cause short filter runs.

Table 4.1 Runs Performed During 1992

RUN#	DATE	TEST
1	6/22	$FeCl_3$ = 8.5 mg/l, Polymer = 3.0 mg/L, Int Ozone
2	6/23	$FeCl_3$ = 8.5 mg/l, Polymer = 3.0 mg/L, No Ozone
3	6/24	$FeCl_3$ Dose Varied, No Polymer, No Ozone
4	6/25	$FeCl_3$ = 19 mg/L, No Polymer, No Ozone
5	6/26	$FeCl_3$ = 19 mg/L, No Polymer, Int Ozone
6	7/2	Recycle: R = 9.5, 8.0, 6.0, 5.0 %
7	7/7	DAF Loading Rate: Q_0 = 45, 50 gpm
8	7/8	Filter Loading Rate: V_o = 3.0 gpm/ft^2
9	7/9	Filter Loading Rate: V_o = 4.5 gpm/ft^2
10	7/10	Filter Loading Rate: V_o = 6.0 gpm/ft^2
11	7/13-7/15	Sludge Removal Rate: Once Every 1, 3, 8, and 24 hrs
12	7/27	GAC vs Anthracite Filter
13	7/28	Flocculation Time = 16 min
14	7/29	Flocculation Time = 8 min
15	8/11	Pre Ozonation vs Air Only vs No Air, No Ozone
16	8/12	Flocculation Time = 8 min, V_o = 4.5 gpm/ft^2
17	8/13-8/14	Flocculation Time = 16 min, V_o = 4.5 gpm/ft^2
18	10/23-10/24	Pre Ozonation vs No Ozone, No Caustic, V_o = 4.5 gpm/ft^2, Comparison to DF train
19	10/24	Flocculation Time = 16 min, V_o = 4.5 gpm/ft^2, No Caustic
20	10/25	Flocculation Time = 8 min, V_o = 4.5 gpm/ft$^{2;}$, No Caustic

Note: R = Recycle Ratio; V_o=Filter Loading Rate

Coagulation by ferric chloride in direct filtration produces ferric hydroxide ($Fe(OH)_3$ (s)) that can similarly cause short filter runs.

The WRTP utilizes ferric chloride and the cationic polymer Floxan 5062 as primary coagulants, which results in effective treatment at reasonable headloss development. Experiments were performed during July of 1993 to evaluate DAF performance at coagulation conditions similar to the WRTP and for coagulation by ferric chloride alone. Presented below are results from two jar tests and pilot runs # 2, 3, and 4. The jar test was performed to determine the range of effective treatment by ferric chloride alone. Pilot run #3 examined four ferric chloride coagulant dosages using the DAF pilot plant. Pilot runs #2 and #4 examined DAF treatment utilizing ferric chloride with polymer at WRTP dosages (run #2) and utilizing the optimum ferric chloride dose determined in run #3 (run #4). (Note: runs #1 and #5 evaluated these coagulant conditions with ozonation after flotation (intermediate ozone) and are presented in section 4.1.4).

4.1.1.1 No Polymer Condition: Jar Test

The $FeCl_3$ dose (with no polymer) for effective DAF treatment of West River source water was first evaluated during two jar tests performed on June 17, 1992. Raw water for the tests was collected at the WRTP on June 16, 1992. The jar tests were performed at UMass using the Aztec DAF bench scale system described previously. A control jar was dosed at 8 mg/L $FeCl_3$ and 3.0 mg/L polymer (as product). Test jars were dosed with 8 to 32 mg/L $FeCl_3$ in 4 mg/L increments. Operating conditions for the jar tests were: water temperature, 22°C; coagulation pH, 6.7 ± 0.2; flocculation time, 16 minutes; mixing intensity (G), 55 s^{-1} (100 rpm @

22°C); 'recycle ratio', 8 percent; and flotation time, 10 minutes. Raw water conditions were: turbidity, 2.3 ntu; UV254, 0.123 cm^{-1}; and pH, 6.74.

Figure 4.1 presents jar test results as turbidity and fraction of raw water UV254 versus coagulant dosage. Ferric chloride with polymer produced a clarified water (after flotation) with turbidity of 0.61 ntu and 30 percent of the raw water UV254. Without polymer, ferric chloride dosages of 8 mg/L and 12 mg/L produced turbidities above 2.0 ntu with no significant UV removal. Ferric chloride dosages of 16 mg/L and 20 mg/L produced clarified water with turbidity below 2.0 ntu and removed 66 and 61 percent of the raw water UV254 respectively. Ferric chloride dosages of 24-32 mg/L produced water of similar quality as treatment by ferric chloride with polymer. Based on the successful bench scale results, pilot studies were performed evaluating coagulation by ferric chloride alone.

4.1.1.2 No Polymer Condition: Pilot Run #3

The optimum ferric chloride dose for the pilot plant was determined during run #3 on June 24, 1992. Operating conditions and raw water quality for run #3 are presented in Table 4.2. Ferric chloride was tested at the WRTP dose and 1.5, 2.0, and 2.5 times the WRTP dose, which resulted in applied ferric chloride dosages of 9.3, 12.8, 19.1 and 23.0 mg/L. The 9.3 mg/L dose was run for two and one half hours following filter backwash. Higher dosages were applied for three and one half hours each. A constant coagulation pH of 6.7±0.2 was maintained by varying the caustic dose.

Figure 4.2 presents results from run #3 in terms of DAF effluent turbidity, DAF train filtered water turbidity and UV254, and filter head loss development with

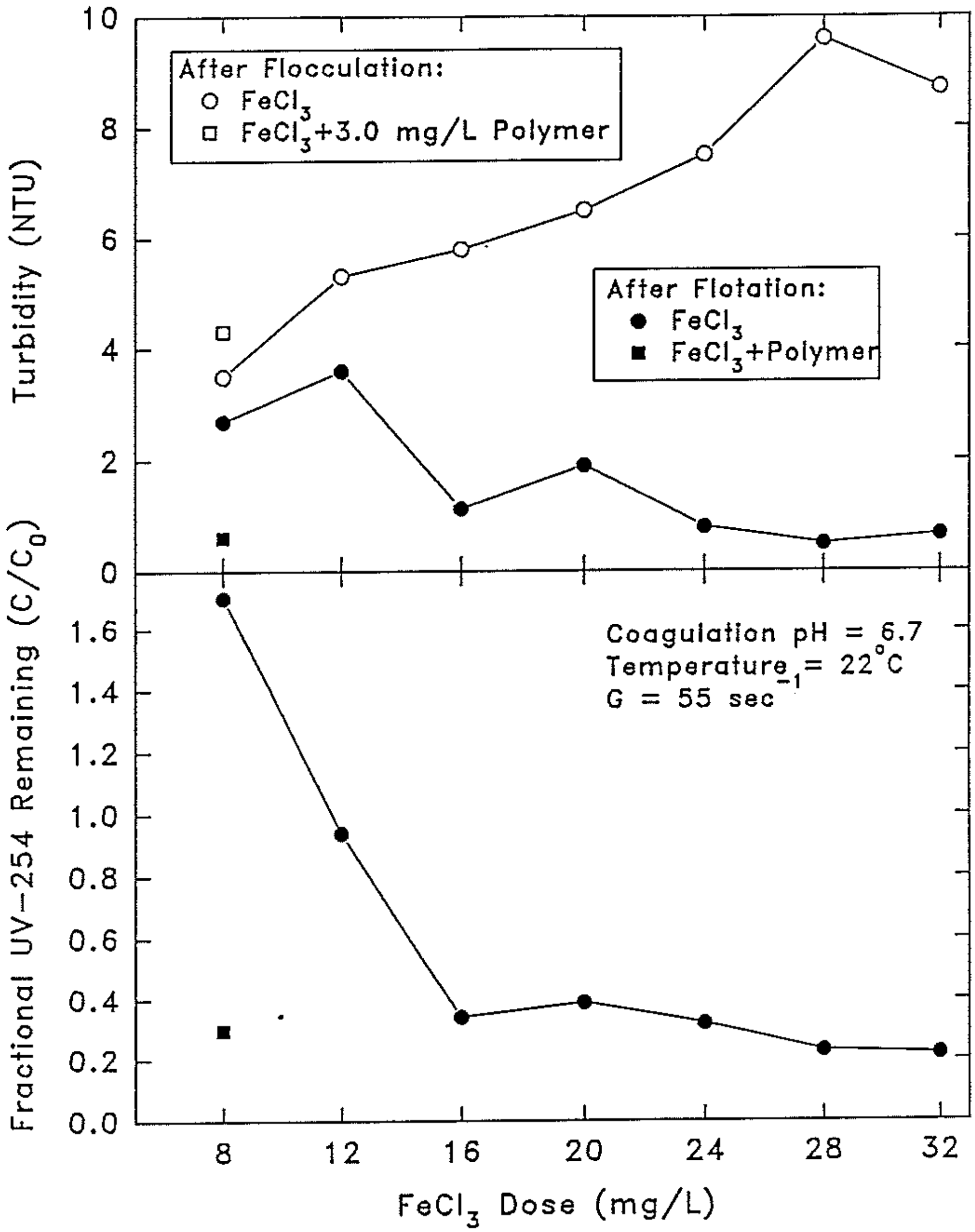


Figure 4.1 Jar Test; Turbidity and Fraction of UV254 vs Ferric Chloride Dose

Table 4.2 **Operating Conditions, Dosages, and Raw Water Data; Run #3, Varying Ferric Chloride Dose**

Parameter	Run #3 (6/24/92)
Operating Conditions	
Recycle Ratio (%)	9.5
Sludge Removal Freq. (1/# hr)	1 / 1 hr
Filter Loading (gpm/ft^2)	3.0
Flocculation Time (min)	16
Chemical and Ozone Dosages	
Ferric Chloride (mg/L)	Varied
Polymer (mg/L)	0.0
Caustic (mg/L)	Varied
Ozone (mg/L)	Off
Raw Water Characteristics	
Turbidity (ntu)	0.85 (0.78-0.98)
UV254 (cm^{-1})	0.106 (0.104-0.108)
pH	6.8 (6.7-7.0)

time. The UV254 data are plotted as the fractional UV254 remaining (i.e., effluent UV254 divided by the raw water UV254). The head loss data are plotted as the total head loss across the filter media in feet of water.

Examination of the results in Figure 4.2 shows that steady state for each condition was reached after one to one and one half hours. At 9.3 mg/L applied ferric chloride, DAF effluent turbidity was above 1.0 ntu, DAF filtered water turbidity was as high as 0.69 ntu and UV254 values were twice that the of raw water. At 12.8 mg/L applied ferric chloride, clarified and filtered water turbidities averaged

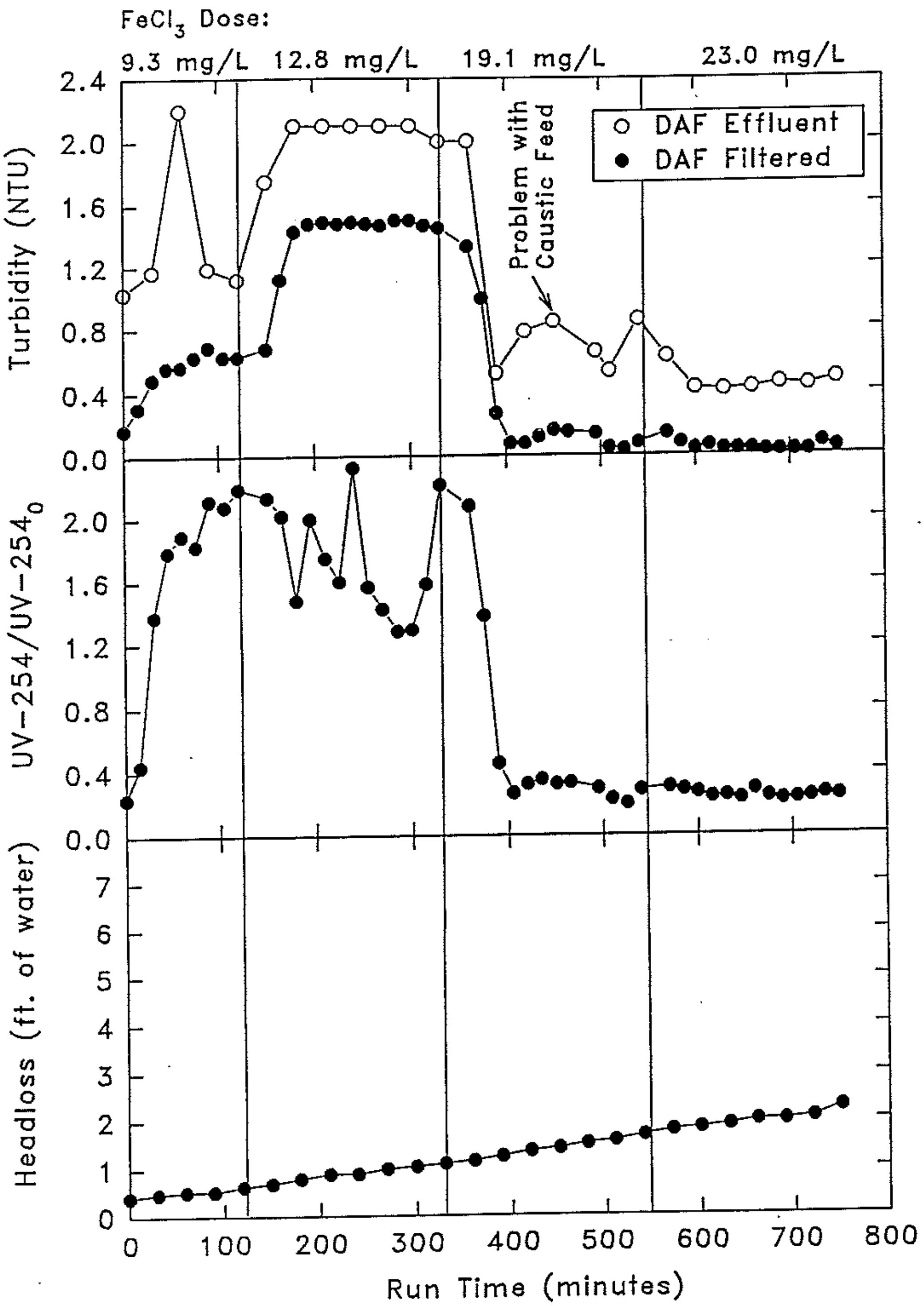


Figure 4.2 **DAF and Filtered Water Quality; Run #3, Varying Ferric Chloride Dose**

2.1 ntu and 1.48 ntu respectively and filtered UV254 values varied from 1.3 to 2.4 times that of raw water. Increasing the dose to 19.1 mg/L provided effective treatment as measured by average clarified and filtered turbidities of 0.73 ntu and 0.10 ntu respectively, and 74 percent UV254 removal through treatment with minor variability due to a caustic feed problem. Application of ferric chloride at 23.0 mg/L consistently produced clarified water with turbidity less than 0.5 ntu, filtered water with turbidity less than 0.05 ntu and 75 percent and higher UV254 removals. Based upon these results, a ferric chloride dose (no polymer) twice that of the WRTP ferric chloride dose (with polymer) was applied for Run #4.

4.1.1.3 Polymer vs No Polymer: Pilot Run #2 vs #4

Run #2 was conducted on June 23, 1992 using the ferric chloride and polymer dosages of the WRTP with no ozone applied. Run #4 was conducted using ferric chloride alone at the dosage determined in Run #3. This resulted in dosages of 8.5 mg/L ferric chloride and 2.8 mg/L polymer (as product) during Run #2 and 18.5 mg/L ferric chloride during run #4. All other operating conditions, shown in Table 4.3, were held constant for both runs. Raw water quality for both days was similar as measured by turbidity, UV254, and pH (Table 4.3).

Figure 4.3 shows turbidity, fraction of raw water UV254 and headloss development over run time for both runs. Steady state was reached for the ferric chloride with polymer condition after 1 hour. Steady state for the ferric chloride alone condition was achieved after three hours due to pH control problems. Both coagulant conditions resulted in similar effective treatment as measured by filtered water turbidities consistently below 0.08 ntu and 70 percent and better UV254

Table 4.3 Operating Conditions, Dosages, and Raw Water Data; Run #2, Ferric Chloride With Polymer; Run #4, Ferric Chloride With No Polymer

Parameter	Run #2 (6/23/92)	Run #4 (6/25/92)
Operating Conditions		
Recycle Ratio (%)	9.5	9.5
Sludge Removal Freq. (1/# hr)	1 / 1 hr	1 / 1 hr
Filter Loading (gpm/ft^2)	3.0	3.0
Flocculation Time (min)	16	16
Chemical and Ozone Dosages		
Ferric Chloride (mg/L)	8.8	18.5
Polymer (mg/L)	2.8	0.0
Caustic (mg/L)	5.8	8.8
Ozone (mg/L)	Off	Off
Raw Water Characteristics		
Turbidity (ntu)	0.95 (0.83-1.15)	0.99 (0.82-1.26)
UV254 (cm^{-1})	0.103 (0.100-0.105)	0.108 (0.105-0.110)
pH	6.9	6.7 (6.5-6.8)

removals. Filter headloss data showed increased headloss development when ferric chloride alone was used. Filter headloss for the ferric chloride with polymer condition increased at a rate of 0.9 inches/hour (in/hr). The filter headloss development rate for the ferric chloride condition was 1.8 in/hr after steady state was reached.

Average steady state turbidity and UV254 values across treatment for each run are presented in Table 4.4. The numbers are averages of three samples taken throughout each run. Turbidity, UV254 and pH through treatment were similar for

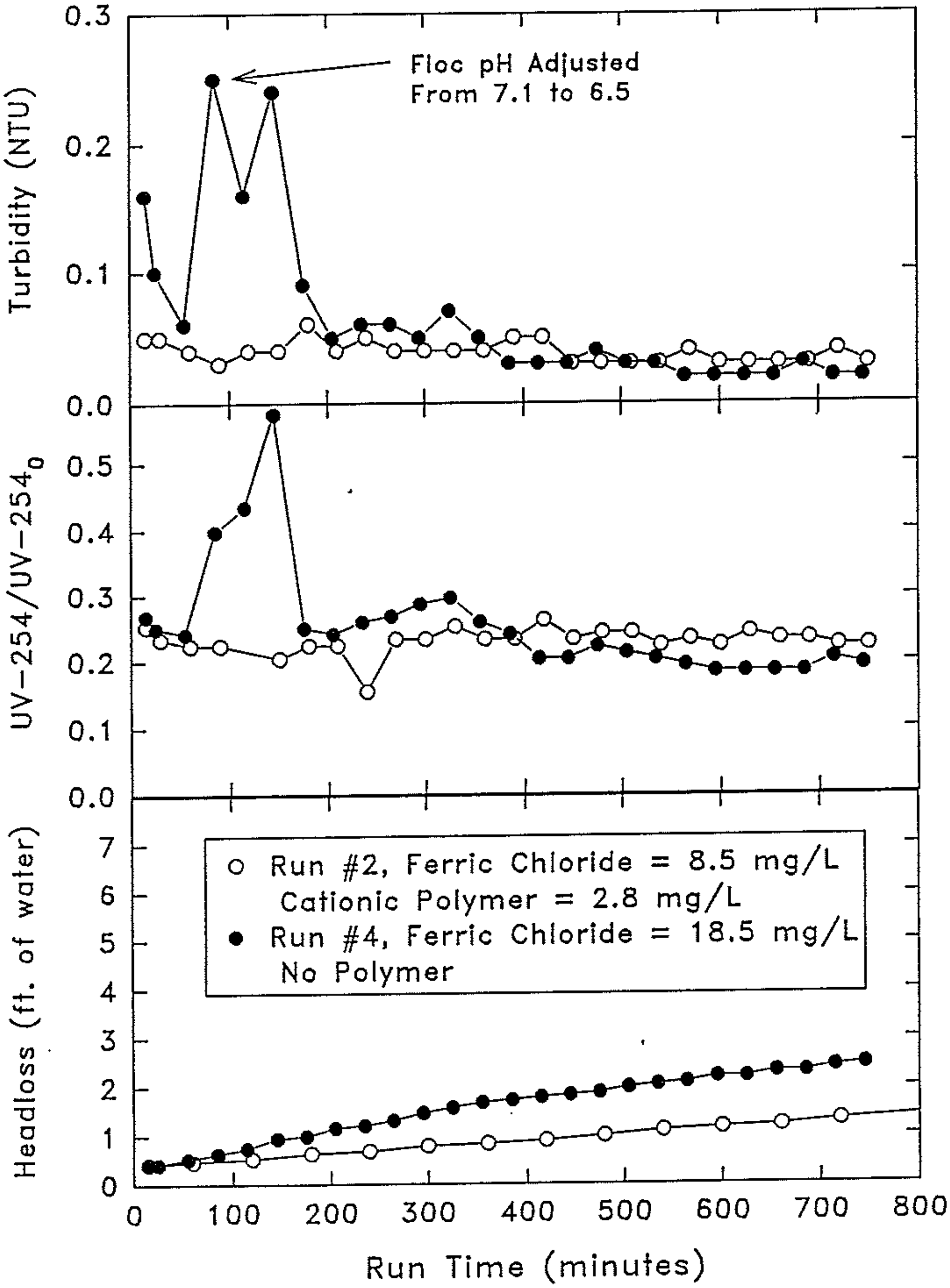


Figure 4.3 Filtered Water Quality; Run #2, Ferric Chloride With Polymer; Run #4, Ferric Chloride With No Polymer

the two runs with the following exceptions. The pHs through treatment were approximately 0.2-0.3 pH units higher in run #2 than in run #4. The flocculation sample for the ferric chloride alone condition (run #4) was higher in turbidity than for the ferric chloride with polymer condition (run #2) (1.7 ntu vs 1.3 ntu). Also, the turbidity was higher after flotation with coagulation by ferric chloride alone than with ferric chloride with polymer (0.76 ntu vs 0.60 ntu).

Table 4.4 Turbidity, UV254 and pH Across Treatment; Run #2, Ferric Chloride With Polymer; Run #4, Ferric Chloride With No Polymer

Location	Turbidity (ntu)		UV254 (cm^{-1})		pH	
	Run #2	Run #4	Run #2	Run #4	Run #2	Run #4
Raw Water	0.95	0.89	0.103	0.107	6.9	6.6
Ozone-Pre	Off	Off	Off	Off	Off	Off
Floc	1.3	1.7	--	--	6.7	6.5
DAF Effl	0.60	0.76	0.027	0.027	6.9	6.6
DAF Filt	0.04	0.03	0.023	0.024	6.9	6.7

Note: All values represent averages of three values.

Dissolved organic carbon (DOC) values versus sample location are presented in Figure 4.4. The main graph shows fraction of raw water DOC; the inset presents absolute DOC values. Values represent averages of two samples taken throughout the run. DOC removal for each condition was similar with slightly better treatment on run #4 (ferric chloride alone). With ferric chloride and polymer, flotation removed 45 percent of the raw water DOC and subsequent filtration removed an additional 10

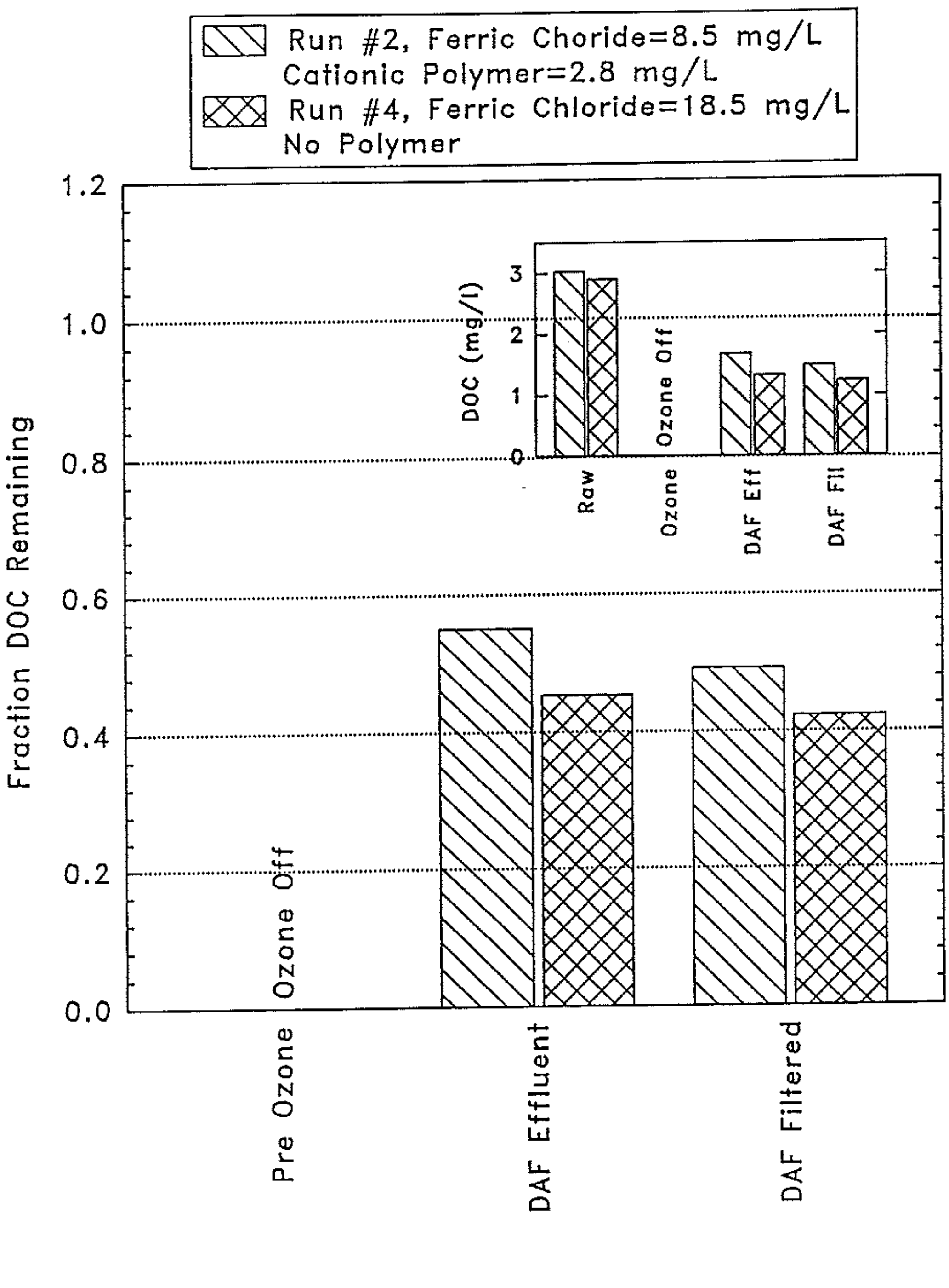


Figure 4.4 DOC Results for Runs #2 and #4

percent. With ferric chloride alone, DOC removals were 50 percent after flotation and 58 percent after filtration.

Total particle counts, particle number average diameter, and particle volume average diameter across treatment for runs #2 and #4 are presented in Table 4.5.

Table 4.5 Particle Counts Across Treatment; Run #2, Ferric Chloride With Polymer; Run #4, Ferric Chloride With No Polymer

Location	Total Particles (#/mL)		Number Average Diameter (μm)		Volume Average Diameter (μm)	
	Run #2	Run #4	Run #2	Run #4	Run #2	Run #4
Raw Water	3980	3154	4.4	4.3	7.7	7.3
Ozone-Pre	Off	Off	Off	Off	Off	Off
Floc	1965	2089	5.3	5.2	12.3	11.4
DAF Effl	659	370	4.1	4.2	8.5	9.6
DAF Filt	60	18	4.7	5.8	9.1	11.3

Both coagulant conditions resulted in effective removal of particles by flotation and filtration. After flotation, total particle counts were 659 /mL for ferric chloride with polymer and 370 /mL for ferric chloride alone. These results differed from turbidity measurements where the ferric chloride alone condition resulted in higher clarified water turbidity. Following filtration, particle counts were 60 /mL and 18 /mL for the ferric chloride and polymer, and the ferric chloride alone conditions respectively.

4.1.1.4 Discussion

Based upon both jar tests and one pilot run, the required ferric chloride dose for effective treatment was at least twice the required ferric chloride dose with 2-3 mg/L of polymer. Turbidity and UV removal for flotation and filtration increased slightly at higher dosages. Runs #2 and #4, which compared treatment by ferric chloride with polymer and ferric chloride alone showed similar overall removals of particles, as measured by turbidity and particle counts, and similar removal of organics as measured by UV254 and DOC. DOC results for the two coagulation conditions were similar, with slightly better overall removal with coagulation by ferric chloride alone than with coagulation by ferric chloride with polymer.

The rate of filter headloss development was low for both coagulant conditions but ferric chloride alone resulted in a filter headloss development rate almost twice that of ferric chloride with polymer. Particle count and turbidity data showed higher particle loadings to the flotation unit for the ferric chloride alone condition. After flotation, the measured turbidity was higher for the ferric chloride alone condition but the total particle number was lower. The turbidity and particle count data suggest a larger number of submicron particles (less than 1 μm in diameter) after flotation for the ferric chloride alone condition than the ferric chloride with polymer condition. Particles smaller than 1 μm are primarily removed by Brownian diffusion in filtration and for the same mass of particulate matter, particles smaller than 1 μm in diameter cause more rapid headloss development than larger particles (Tobiason *et al.* (1993b)). The increased headloss development for the ferric chloride alone condition could be due in part to the pH problems at the beginning of the run.

Evaluation of the coagulant costs of the two coagulation options discussed above shows the use of ferric chloride alone would result in significant cost savings in coagulants compared to ferric chloride with polymer. For the SCCRWA, the cost of $FeCl_3$ is \$0.059 /lbs and \$0.78 /lbs for polymer. At the coagulant dosages used during run #2, the cost of the $FeCl_3$ is \$0.0042 /1000 gallons and the cost of the polymer is \$0.018 /1000 gallons. At the coagulant dose used during run #4, the cost of the $FeCl_3$ is \$0.0092 /1000 gallons. To treat 10 million gallons per day, the coagulant cost of the ferric chloride with polymer option would be \$220 per day and the ferric chloride alone option would cost \$92 per day.

4.1.2 Effects of Recycle

Recycle in DAF is defined as the fraction of flow returned to the saturator for air entraining. Increased recycle flows (at constant saturator pressure) increases bubble-particle collision opportunities. Results from pilot run #6 in which four recycle ratios were examined are presented below.

<u>4.1.2.1 Varying Recycle Ratio: Pilot Run #6</u>

Prior to July 2, 1992, the DAF pilot plant was operated at a conservative recycle ratio of 9.5 percent. Recycle ratios of 9.5, 8.0, 6.0 and 5.0 percent were evaluated during run #6 on July 2, 1992. Throughout the run, the saturator pressure was a constant 75 psig. Table 4.6 contains operating conditions and raw water quality for run #6.

Two noteworthy operational changes occurred during run #6: 1) Intermediate ozonation (ozonation after flotation) was discontinued after the first hour of the run due to unacceptably high filtered water turbidity; the most probable cause of the high turbidity was oxidation and precipitation of manganese (see section 4.1.6) and 2) the recycle injection needle valves on the DAF unit were flushed while the 5.0 percent recycle condition was being evaluated (see below).

Table 4.6 Operating Conditions, Dosages, and Raw Water Data; Run #6, Varying Recycle Ratio

Parameter	Run #6 (7/2/92)
Operating Conditions	
Recycle Ratio (%)	Varied
Sludge Removal Freq. (1/# hr)	1 / 1 hr
Filter Loading (gpm/ft^2)	3.0
Flocculation Time (min)	16
Chemical and Ozone Dosages	
Ferric Chloride (mg/L)	8.7
Polymer (mg/L)	2.8
Caustic (mg/L)	4.1
Ozone (mg/L)	Off
Raw Water Characteristics	
Turbidity (ntu)	0.81 (0.60-1.24)
UV254 (cm^{-1})	0.103 (0.096-0.108)
pH	6.6 (6.5-6.7)

Figure 4.5 presents results from run #6 in terms of turbidity and UV254 after flotation and filtration and filter head loss development versus time. For all recycle ratios, the DAF train filtered water turbidity was 0.01 to 0.02 ntu and UV254 removal through filtration was 77 to 82 percent. With 9.5 and 8.0 percent recycle ratios, DAF clarified water had an average turbidity of 0.52 ntu. The 6.0 percent recycle ratio resulted in steadily decreasing DAF performance as measured by a turbidity increase from 0.51 ntu to 1.23 ntu over three hours. Decreasing the recycle ratio to 5.0 percent further decreased DAF performance resulting in a clarified water

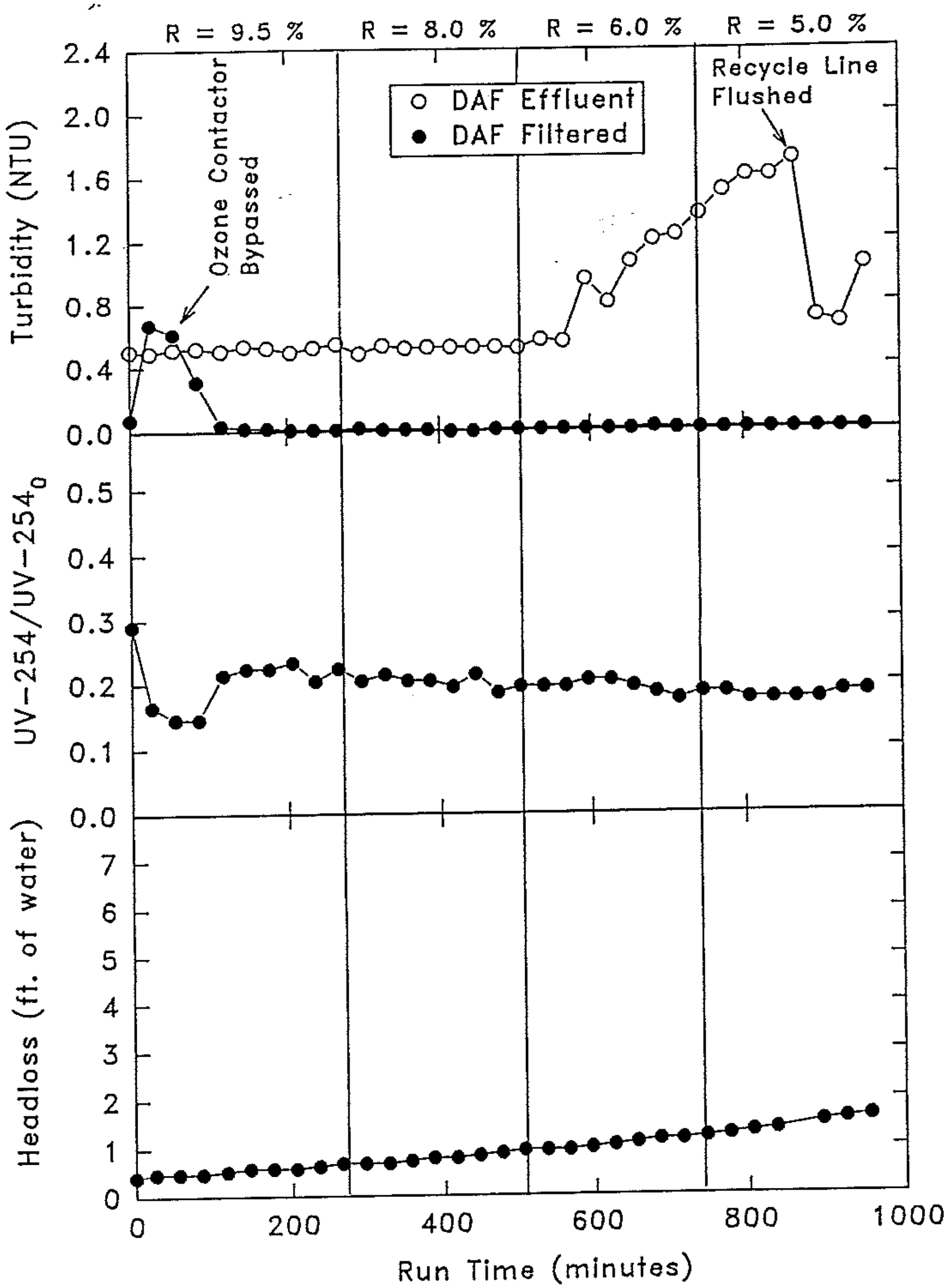


Figure 4.5 DAF and Filtered Water Quality; Run #6, Varying Recycle Ratio

turbidity as high as 1.7 ntu. Before the needle valves were flushed, very few bubbles were observed in the flotation tank at 5.0 percent recycle. After the recycle needle valves were flushed, more bubbles were observed in the flotation tank and the clarified water turbidity decreased to a more acceptable value of 0.66 ntu. The best explanation for the poor turbidity results after flotation at the 6.0 and 5.0 percent recycle is clogging of the needle valves at low recycle flows.

Filter headloss increased at a rate of 0.9 in/hr over the 14 hours the filter run was observed. Differences in filter headloss development for each recycle condition are difficult to quantify given the limited duration of each test condition. Observation of Figure 4.5 shows slightly increased headloss development during the evaluation of the 5.0 percent recycle ratio. The increases in headloss development correspond to decreases in DAF turbidity removal.

Table 4.7 presents steady state turbidity, UV254 and pH values across treatment for each recycle condition. Values in Table 4.7 represent one measurement. Turbidity, UV254 and pH were similar for each recycle condition with the exception of DAF clarified water turbidity, which increased at lower recycle ratio. DAF removal of dissolved organic matter as measured by UV254 was consistent at all recycle flows despite the poor turbidity removal by DAF at low recycle flows. DOC measurements were not taken during run #6.

Table 4.8 presents total particle counts, particle number average diameter, and particle volume average diameter across treatment for run #6. Particle removal through the DAF treatment train was excellent for all recycle conditions (all filtered water particle counts below 20 /mL). At recycle ratios of 9.5 and 8.0 percent, total

Table 4.7 Turbidity, UV254 and pH Across Treatment; Run #6, Varying Recycle Ratio

Location	Turbidity (ntu)		UV254 (cm^{-1})		pH	
	R=9.5	R=8.0	R=9.5	R=8.0	R=9.5	R=8.0
Raw Water	0.60	1.24	0.104	0.108	6.7	6.5
Ozone-Pre	Off	Off	Off	Off	Off	Off
Floc	1.6	1.5	--	--	6.5	6.5
DAF Effl	0.54	0.52	0.023	0.023	6.6	6.5
DAF Filt	0.01	0.01	0.021	0.022	6.8	6.7
Location	Turbidity (ntu)		UV254 (cm^{-1})		pH	
	R=6.0	R=5.0	R=6.0	R=5.0	R=6.0	R=5.0
Raw Water	0.71	0.67	0.096	0.103	6.6	6.5
Ozone-Pre	Off	Off	Off	Off	Off	Off
Floc	1.7	1.7	--	--	6.5	6.5
DAF Effl	1.20	0.70	0.021	0.020	6.6	6.5
DAF Filt	0.02	0.01	0.019	0.018	6.8	6.6

particle counts after flotation were 425 /ml and 563 /mL respectively. At 6.0 recycle ratio, particle counts after flotation were 1467 /mL, which represents poor removal when compared to the flocculated sample particle count of 2053 /mL. The increased particle counts after flotation are comparable to the increase in turbidity after flotation and are explained by clogging of the needle valves at low recycle flow. The sample representing the 5.0 percent recycle condition was taken one hour after the recycle needle valves were flushed, and contained 1110 /mL total particles. At 9.5 and 8.0 percent recycle, the number average diameter of particles decreased from 5.6 μm and

Table 4.8 Particle Counts Across Treatment; Run #6, Varying Recycle Ratio

Location	Total Particles (#/mL)			
	R=9.5	R=8.0	R=6.0	R=5.0
Raw Water	1986	2441	3086	4106
Ozone-Pre	Off	Off	Off	Off
Floc	1353	1267	1873	2994
DAF Effl	425	563	1467	1110
DAF Filt	15	13	14	17

Location	Number Average Diameter (μm)				Volume Average Diameter (μm)			
	9.5	8.0	6.0	5.0	9.5	8.0	6.0	5.0
Raw Water	4.2	9.5	4.6	4.6	7.0	12.3	7.7	8.8
Ozone-Pre	Off	Off	Off	Off	Off	Off	Off	Off
Floc	5.6	5.0	6.0	6.4	11.1	9.8	12.0	14.1
DAF Effl	4.2	4.4	6.0	4.6	8.8	8.1	10.6	10.8
DAF Filt	5.6	4.6	5.4	5.3	14.8	6.4	10.0	9.9

5.0 μm after flocculation to 4.2 μm and 4.4 μm after flotation However, when particulate removal through flotation was poor (i.e., 6.0 percent recycle ratio) the number average diameter of particles after flocculation did not change through flotation (6.0 μm after flocculation and after flotation).

4.1.2.2 Discussion

Flotation and subsequent filtration provided effective treatment at recycle ratios of 9.5 and 8.0 percent with no observed advantage provided by the higher recycle flow. At 6.0 and 5.0 percent recycle ratio particulate removal by flotation decreased as measured by turbidity and particle counts. The data suggests that clogging of the needle valves at low recycle flows decreased DAF performance. At 5 percent recycle, DAF treatment performance after flushing the needle valves was similar to performance at 9.5 and 8.0 percent. The increased particulate loading to the filters at lower recycle increased filter headloss development but did not affect the filtered water quality. The increases in filter headloss development at lower DAF recycle ratio are difficult to quantify due to the limited time each recycle flow was evaluated.

Work by Zabel (1984; 1985) and Longhurst and Graham (1987) and Edzwald and co-workers suggest treatment of a low turbidity, moderately colored surface water can be effective by DAF at recycle ratios as low as 5 percent at saturator conditions similar to those used in this study. Also, Kaminski *et al.* (1991) reported effective flotation of Lake Whitney source water, a water similar in quality to the WRTP source water, using recycle ratios as low as 5 percent. The pilot plant used by Kaminski *et al.* was the same plant used for the research in this report.

4.1.3 Effects of Filter Loading

DAF was examined as a method of plant expansion where solids removal by DAF would allow for an increased filter hydraulic loading at the WRTP and therefore increased plant capacity. Three consecutive pilot runs were performed at increasing filter hydraulic loading to evaluate treatment performance.

4.1.3.1 Increasing Filter Loading: Pilot Runs #8, #9, and #10

Run #8, conducted on July 8, 1992, was the control condition where the DAF pilot plant was operated with a filter loading of 3.0 gpm/ft^2. The filter loading was increased to 4.5 gpm/ft^2 on July 9, 1992 (run #9) and to 6.0 gpm/ft^2 on July 10, 1992 (run #10). Table 4.9 presents operating conditions, dosages, and raw water data for the three runs. Except for the filter loading rates, all operating conditions and dosages were constant for all three runs. Raw water quality for all three days was similar as measured by turbidity, UV254, and pH (Table 4.9).

Figure 4.6 presents DAF filtered water turbidity, fraction of raw water UV254 and filter headloss development over run time for all three runs. Steady state for all three runs was reached after one hour. The three filter loading rates resulted in similar effective treatment as measured by filtered water turbidities consistently below 0.08 ntu and 75 percent and better UV254 removals. Filtered water turbidity during the 6.0 gpm/ft^2 filter loading rate steadily decreased from 0.07 ntu after 1 hour into the run to 0.02-0.03 ntu after 12 hours. At increased filter loading rate, both the empty bed filter headloss and filter headloss development were significantly higher. At filter hydraulic loadings of 3.0, 4.5, and 6.0 gpm/ft^2 , the empty bed filter headlosses were 3 inches, 11 inches and 13 inches respectively and the filter headloss increased at rates of 1.4 in/hr, 2.6 in/hr and 3.5 in/hr respectively. Projecting to eight feet of headloss, the unit filter run volumes (UFRVs) are 12100, 8800 and 8400 $gal/ft^2/run$ respectively with filter loadings of 3.0, 4.5 and 6.0 gpm/ft^2.

Table 4.9 Operating Conditions, Dosages, and Raw Water Data; Runs #8, #9, & #10, Varying Filter Loading Rate

Parameter	Run #8 (7/8/92)	Run #9 (7/9/92)	Run #10 (7/10/92)
Operating Conditions			
Recycle Ratio (%)	8.0	8.0	8.0
Sludge Removal Freq. (1/# hr)	1 / 1 hr	1 / 1 hr	1 / 1 hr
Filter Loading (gpm/ft^2)	3.0	4.5	6.0
Flocculation Time (min)	16	16	16
Chemical and Ozone Dosages			
Ferric Chloride (mg/L)	8.6	8.8	8.9
Polymer (mg/L)	2.6	2.8	2.8
Caustic (mg/L)	7.3	7.3	7.3
Ozone (mg/L)	1.5-Pre	1.5-Pre	1.5-Pre
Raw Water Characteristics			
Turbidity (ntu)	0.78 (0.74-0.84)	0.80 (0.68-0.95)	0.86 (0.81-0.90)
UV254 (cm^{-1})	0.108 (0.105-.111)	0.110 (0.108-0.112)	0.106 (0.103-0.108)
pH	6.6 (6.5-6.7)	6.6 (6.6-6.6)	6.6 (6.6-6.6)

Table 4.10 contains average steady state turbidity, UV254 and pH measurements at multiple locations on the pilot train during runs #8, #9, and #10. Values represent averages of three or four measurements. The values through pre-ozonation, flocculation and flotation are similar for each run.

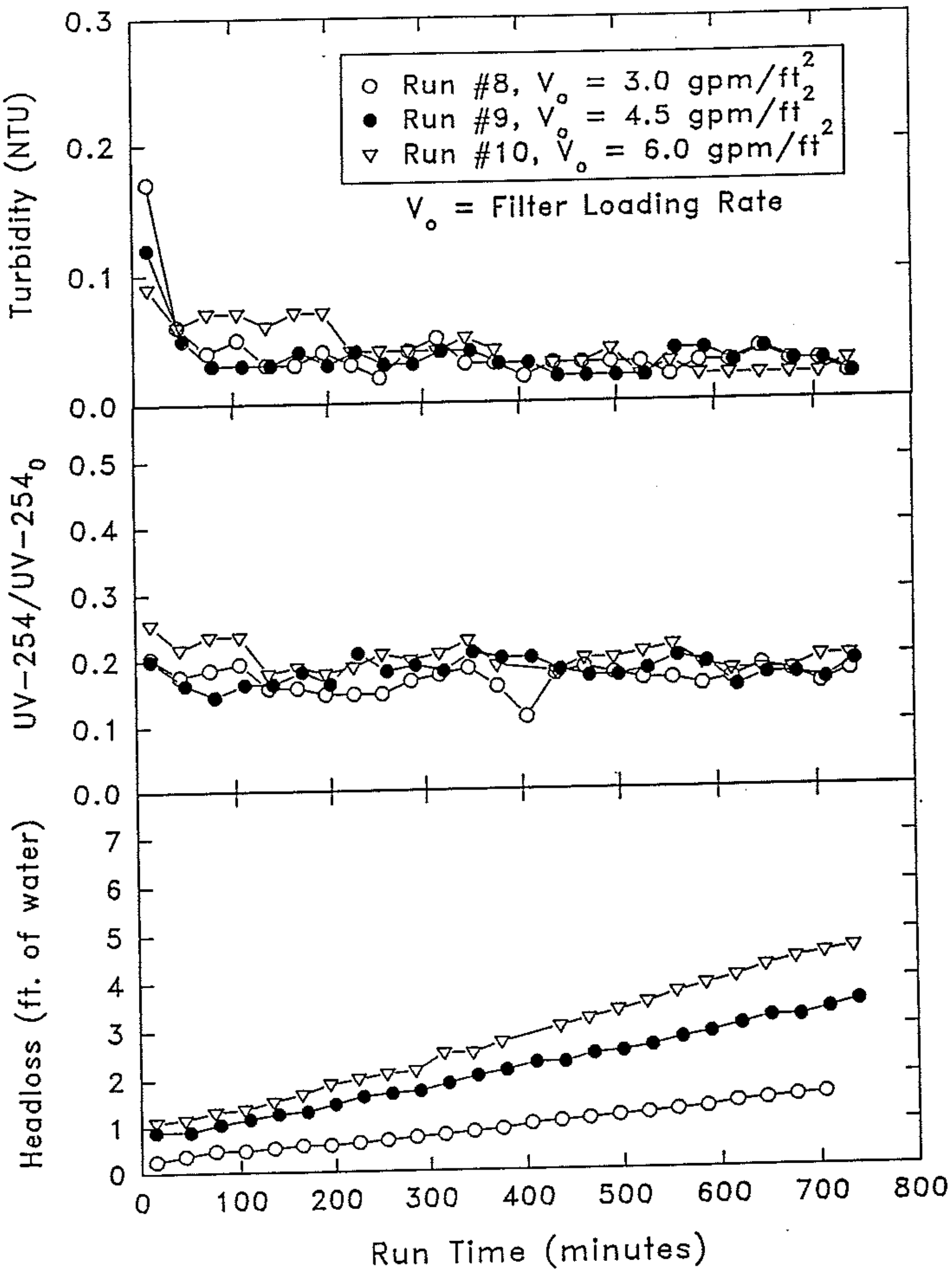


Figure 4.6 **Filtered Water Quality; Runs #8, #9, and #10, Varying Filter Loading Rate**

Table 4.10 Turbidity, UV254 and pH Across Treatment; Runs #8, 9, & 10, Varying Filter Loading Rate

Location	Turbidity (ntu)			UV254 (cm^{-1})		
	V_o=3.0	V_o=4.5	V_o=6.0	V_o=3.0	V_o=4.5	V_o=6.0
Raw Water	0.77	0.81	0.86	0.108	0.110	0.106
Ozone-Pre	0.92	0.91	1.00	0.087	0.090	0.088
Floc	2.3	2.6	3.2	--	--	--
DAF Effl	0.81	0.80	0.84	0.022	0.023	0.023
DAF Filt	0.02	0.03	0.03	0.019	0.020	0.020

Location	pH		
	V_o=3.0	V_o=4.5	V_o=6.0
Raw Water	6.6	6.6	6.6
Ozone-Pre	6.6	6.6	6.7
Floc	6.6	6.6	6.7
DAF Effl	6.7	6.7	6.7
DAF Filt	6.6	6.8	6.7

Note: V_o=3.0, V_o=6.0, Values represent averages of three measurements
V_o=4.5, Values represent averages of four measurements

DOC concentrations and fractions of raw water DOC versus sample location for runs #8, #9, and #10 are shown in Figure 4.7. Values represent averages of two measurements taken at different times during the run.. DOC removals through treatment (filtered water) were similar for all conditions, with 50 and 51 percent removals for the 3.0 and 4.5 gpm/ft^2 filter hydraulic loading rates respectively and 44 percent removal for the 6.0 gpm/ft^2 loading rate.

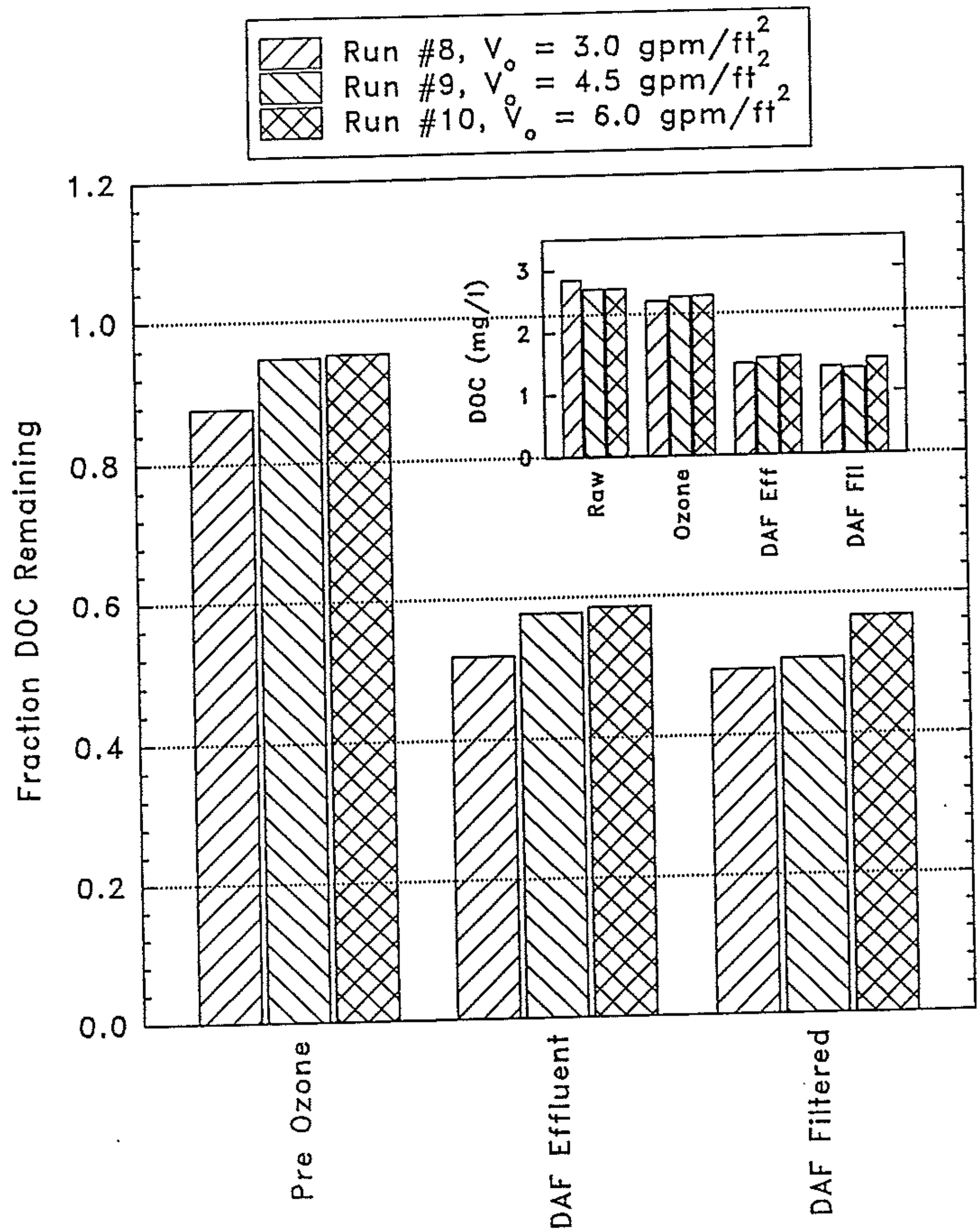


Figure 4.7 DOC Results for Runs #8, 9, & 10

Particle counts were taken across treatment one time for each filter loading rate evaluated. As with turbidity measurements, the particle count data prior to filtration was similar over all three days. After filtration, total particle counts were 20, 25, and 9 /mL for filter loading conditions of 3.0, 4.5 and 6.0 gpm/ft^2.

4.1.3.2 Discussion

Based upon results from runs #8, 9, & 10, increasing the filter loading rate on the DAF pilot plant from 3.0 gpm/ft^2 to 4.5 and 6.0 gpm/ft^2 had no significant impact on finished water quality as measured by turbidity, particle counts, UV254 and DOC measurements. Increasing the filter loading rate increased both the filter empty bed headloss and the rate of filter headloss development. At 6.0 gpm/ft^2, the rate of headloss development on the DAF filter was a reasonable 3.5 in/hr, which corresponds to a run time of 24 hours to 8 feet of headloss. For a comparison of the DAF and direct filtration trains for runs #8 and #10 see Section 4.2.2, which compares filter performance on the DAF and direct filtration trains.

4.1.4 Effects of Sludge Removal

Sludge removal was provided by intermittent operation of a full-length mechanical scraper. The scraper was operated for approximately 5 minutes every hour prior to run #11. The effect of the frequency of scraper operation on water quality and sludge production was evaluated during run # 11.

4.1.4.1 Varying Sludge Scrape Frequency: Run #11

The mechanical sludge removal scraper was operated at a frequency of once every 1, 3, 8, and 24 hours during run #11 from July 13 - July 15, 1992. The 1, 3, and 8 hour removal frequencies were studied for two cycles each. The 24 hour removal frequency was evaluated for one cycle. The duration of scraper operation was manually controlled until the sludge layer was removed. The resulting duration of sludge scraper operation for the 1, 3, 8 and 24 hour scrape frequencies were 5, 5, 8, and 5 minutes respectively. DAF clarified water turbidity, DAF train filtered water turbidity and UV254 and DAF train filter headloss were measured prior to sludge removal to evaluate the effect of sludge buildup on water quality. Operating conditions, raw water data and raw water characteristics for run #11 are presented in Table 4.11. The raw water quality was similar throughout the run as shown by the narrow range of turbidity, UV254 and pH.

DAF filtered water turbidity and UV254, DAF clarified water turbidity and DAF filter headloss development for run #11 are presented in Figure 4.8. Steady state was reached after two hours. The frequency of sludge removal had no significant effect on treated water quality as measured by filtered water turbidity and UV254 and clarified water turbidity. The filtered water on the DAF train consistently had a turbidity of 0.01 ntu and greater than 75 percent removal of UV254. Clarified water turbidity averaged 0.59, 0.66, 0.64 and 0.72 ntu for the 1, 3, 8, and 24 hour sludge removal frequencies. The calculated rate of headloss development increased slightly as the scrape frequency changed from 1 to 3 to 8 and to 24 hours (0.9, 1.3, 1.5, and 1.8 in/hr respectively). For the 24 hour removal frequency, a few large, visible floc particles were observed in the DAF clarified water sample.

Sludge samples were taken for each sludge removal frequency and analyzed for percent solids concentration. Duplicate sludge samples were collected in plastic

Table 4.11 **Operating Conditions, Dosages, and Raw Water Data; Run #11 Varying Sludge Scrape Frequency**

Parameter	Run #11 (7/13/92-7/15/92)
Operating Conditions	
Recycle Ratio (%)	8.0
Sludge Removal Freq. (1/# hr)	Varied
Filter Loading (gpm/ft^2)	3.0
Flocculation Time (min)	16
Chemical and Ozone Dosages	
Ferric Chloride (mg/L)	8.5
Polymer (mg/L)	2.6
Caustic (mg/L)	6.1
Ozone (mg/L)	15-Pre
Raw Water Characteristics	
Turbidity (ntu)	1.17 (1.09-1.22)
UV254 (cm^{-1})	0.109 (0.107-0.112)
pH	6.6 (6.6-6.6)

containers as the sludge fell into the sludge collection trough during sludge removal. The plastic containers were sealed, refrigerated, and returned to UMass for analysis. Analysis consisted of transfer to pre-weighed ceramic containers and determination of the mass of the sample before and after drying in a 103°C oven for 24 hours. Results are discussed as the percent weight of solids, which equals the weight of dry solids divided by the weight of wet solids. The weight of solids increased from 2.3 to 3.1 to 3.9 and to 5.5 percent as the sludge removal frequency increased from 1 to 3 to 8 and to 24 hours respectively.

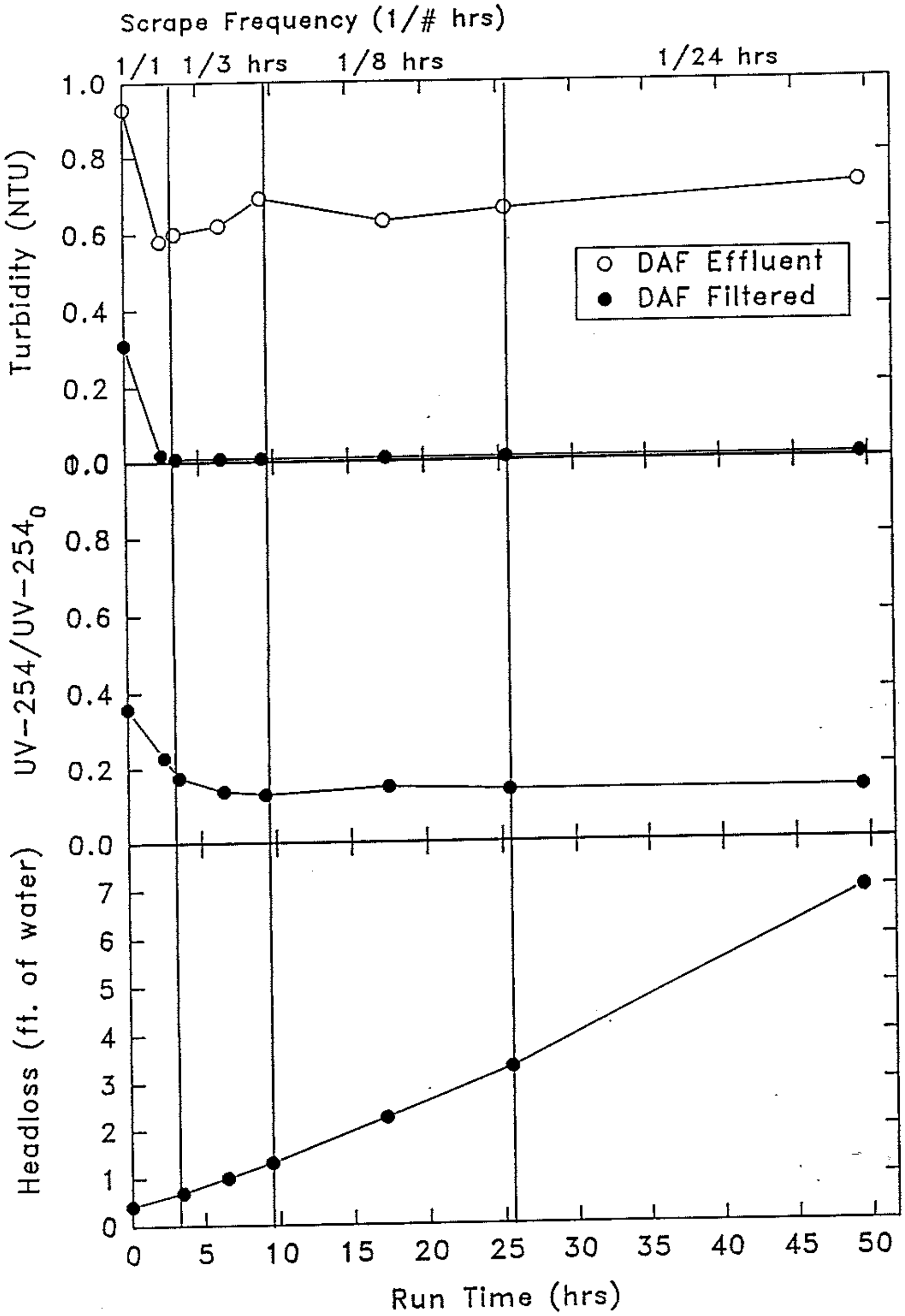


Figure 4.8 DAF and Filtered Water Quality; Run #11, Varying Sludge Scrape Frequency

Table 4.12 presents turbidity, UV254, and pH across treatment for each test condition during run #11. The turbidity, UV254 and pH were similar through treatment for the 1, 3, 8 and 24 sludge removal frequencies. Particle counts taken for the 1, 3, 8 and 24 hour sludge removal frequencies were 498, 818, 549, and 655 /mL after flotation, respectively, and 11, 8, 14, and 8 /mL after filtration respectively.

Table 4.12 Turbidity, UV254 and pH Across Treatment; Run #11, Varying Sludge Scrape Frequency

Location	Turbidity (ntu)				UV254 (cm^{-1})			
	1 / 1 hr	1 / 3 hrs	1 / 8 hrs	1 / 24 hrs	1 / 1 hr	1 / 3 hrs	1 / 8 hrs	1 / 24 hrs
Raw Water	1.18	1.22	1.19	1.09	0.108	0.107	0.107	0.112
Ozone-Pre	1.19	1.06	1.31	1.15	0.089	0.086	0.090	0.091
Floc	3.0	4.6	2.1	3.5				
DAF Effl	0.60	0.69	0.66	0.72	0.020	0.018	0.019	0.020
DAF Filt	0.01	0.01	0.01	0.01	0.019	0.014	0.015	0.015

Location	pH			
	1 / 1 hr	1 / 3 hrs	1 / 8 hrs	1 / 24 hrs
Raw Water	6.6	6.6	6.6	6.6
Ozone-Pre	6.6	6.6	6.7	6.7
Floc	6.6	6.6	6.6	6.6
DAF Effl	6.6	6.6	6.7	6.8
DAF Filt	6.7	6.6	6.8	6.9

4.1.4.2 Discussion

The results of run #11 show that the sludge blanket created by intermittent operation of the mechanical sludge removal system had no significant effects on overall treatment performance of the DAF train. After 24 hours of sludge buildup a small number of large floc particles were observed in the clarified water sample suggesting breakup of the accumulated sludge layer prior to sludge removal. Filtered water quality was unaffected by the sludge removal frequency and filtered headloss development increased slightly with less frequent sludge removal. These results generally agree with Zabel (1985), who reported no breakup of the sludge layer after 24 hours accumulation of sludge formed from treatment of stored algae laden water, and breakup of the sludge layer after only 30 minutes during treatment of a soft, highly colored water.

During this study, water quality parameters were not measured during operation of the sludge removal mechanism. Longhurst and Graham (1987) reported problems with knockdown of the sludge layer as mechanical sludge scraping blades enter the sludge. Knockdown of the sludge layer was reported to cause a slight deterioration in water clarity during scraping. Further study is required to assess water quality during scraping of the DAF sludge layer.

Based upon successful results during run #11, the sludge removal frequency was changed from once every one hour to once every three hours for the remainder of the study. The duration of scraper operation was kept constant at 5 minutes. No negative impact of the changed sludge removal frequency on DAF or filter performance was observed throughout the remainder of the study.

4.1.5 Effects of Flocculation Time

One reported advantage of DAF is effective treatment with flocculation times shorter than required for conventional settling. Edzwald and co-workers (Edzwald *et al.*, 1990; Malley and Edzwald, 1991) suggest creation of flocs tens of microns in diameter, which can often be achieved with flocculation times as low as 5 minutes depending on raw water quality. To evaluate shorter flocculation times, consecutive 12 hour pilot plant runs at 8 and 16 minutes of flocculation time were performed three times throughout the study. Pilot runs #13 and #14 evaluated flocculation times of 16 and 8 minutes respectively at a filtration rate of 3.0 gpm/ft^2. Pilot runs #16 and #17 evaluated flocculation times of 8 and 16 minutes respectively at a filtration rate of 4.5 gpm/ft^2. Between runs #16 and #17 the raw water quality changed drastically and the particle counter was inoperative for both runs. Therefore runs #19 and #20 were performed to evaluate 16 and 8 minutes of flocculation time at a filter hydraulic loading rate of 4.5 gpm/ft^2.

To evaluate flocculation times of 16 minutes, two flocculation bays in series (8 minutes of detention time each) were utilized with paddle speeds of 12 rpm and 8 rpm respectively. To evaluate 8 minutes of flocculation time, the first flocculation bay was bypassed and the second bay was operated with a paddle speed of 12 rpm.

4.1.5.1. Flocculation Time: Pilot Runs #13 and #14

Run #13 was conducted on July 28, 1992 as a control run with 16 minutes of flocculation time prior to flotation. Run #14 was conducted on July 29, 1992 with 8 minutes of flocculation time. All other pilot plant operating conditions and coagulant dosages (shown in Table 4.13) were held constant for both runs. Raw water quality for both days was similar as measured by turbidity, UV254, and pH (Table 4.13).

Table 4.13 Operating Conditions, Dosages, and Raw Water Data; Run #13, Flocculation Time=16 Minutes; Run #14, Flocculation Time=8 Minutes

Parameter	Run #13 (7/28/92)	Run #14 (7/29/92)
Operating Conditions		
Recycle Ratio (%)	8.0	8.0
Sludge Removal Freq. (1/# hr)	1 / 3 hrs	1 / 3 hrs
Filter Loading (gpm/ft^2)	3.0	3.0
Flocculation Time (min)	16	8
Chemical and Ozone Dosages		
Ferric Chloride (mg/L)	8.6	8.7
Polymer (mg/L)	2.6	3.0
Caustic (mg/L)	4.9	4.2
Ozone (mg/L)	1.5-Pre	1.5-Pre
Raw Water Characteristics		
Turbidity (ntu)	0.81 (0.77-0.86)	0.90 (0.85-1.01)
UV254 (cm^{-1})	0.119 (0.112-0.132)	0.120 (0.116-0.127)
pH	6.7 (6.6-6.8)	6.8 (6.8-6.8)

Figure 4.9 presents turbidity, fraction of raw water UV254 and headloss development versus run time for runs #13 and #14. Steady state was reached for both conditions after approximately 1 hour. Both flocculation times resulted in similar effective treatment as measured by filtered water turbidities consistently below 0.09 ntu and 76 percent and higher UV254 removals. Filter headloss data showed higher

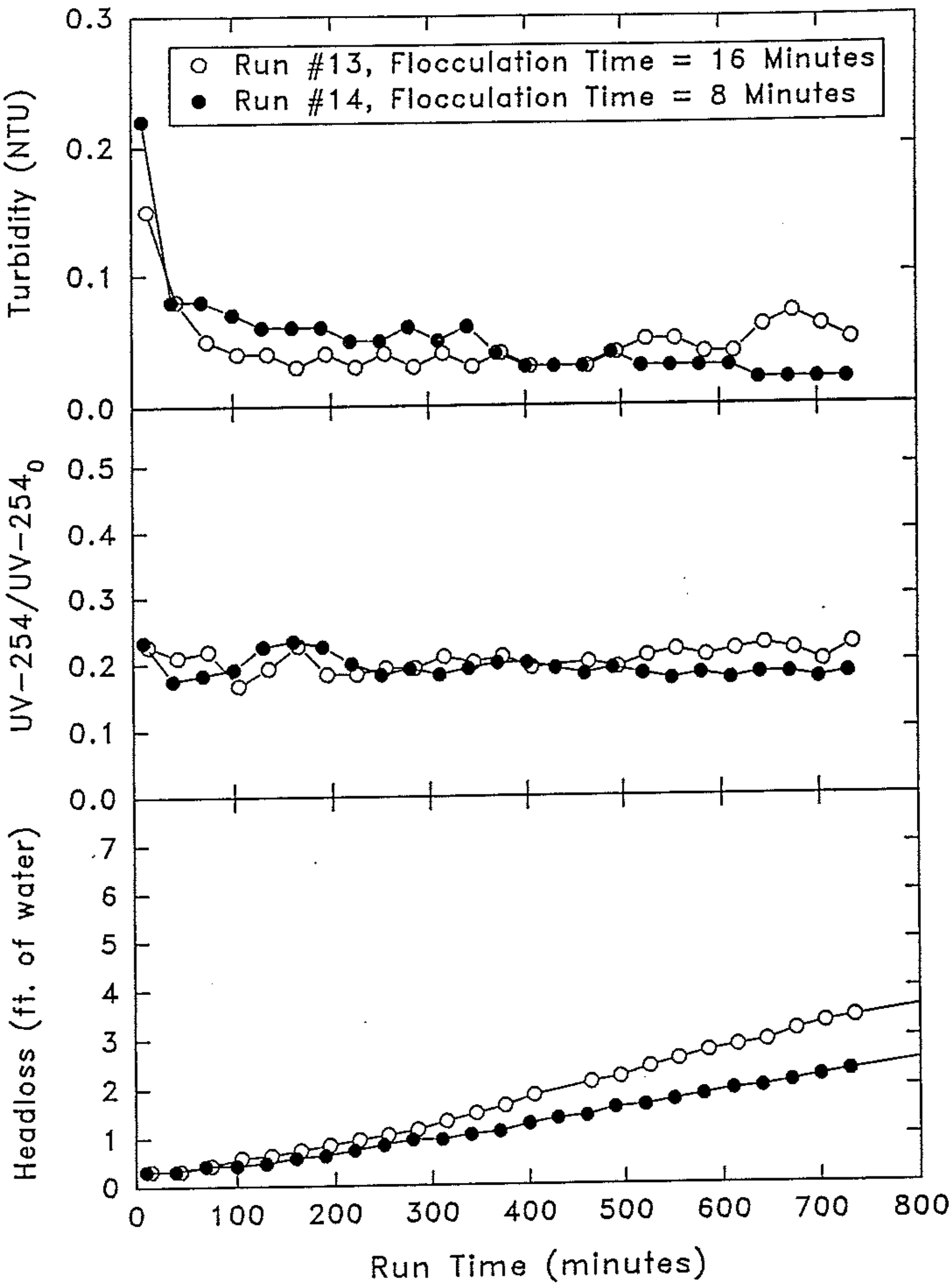


Figure 4.9 **Filtered Water Quality; Run #13, Flocculation Time=16 Minutes; Run #14, Flocculation Time=8 Minutes**

headloss development with 16 minutes of flocculation time than with 8 minutes. Filter headloss development with 8 minutes of flocculation time increased at a rate of 2.1 in/hr over 23 hours and filter headloss development with 16 minutes of flocculation time increased at a rate of 2.8 in/hr over 22 hours.

Average steady state turbidity, UV254 and pH values across treatment for each run are presented in Table 4.14. The values are averages of four samples taken throughout each run. Turbidity, UV and pH through treatment were similar for the two runs with the exception of the DAF effluent turbidity, which increased from 0.7 ntu with 16 minutes of flocculation (Run #13) to 1.20 ntu with 8 minutes of flocculation (Run #14). Also, the flocculation sample with 16 minutes of flocculation was slightly lower in turbidity than with 8 minutes (2.1 ntu vs 2.5 ntu).

Table 4.14 Turbidity, UV254 and pH Across Treatment; Run #13, Flocculation Time=16 Minutes; Run #14, Flocculation Time=8 Minutes

Location	Turbidity (ntu)		UV254 (cm^{-1})		pH	
	Run #13	Run #14	Run #13	Run #14	Run #13	Run #14
Raw Water	0.83	0.91	0.119	0.120	6.7	6.8
Ozone-Pre	0.87	0.88	0.096	0.097	6.7	6.8
Floc	2.1	2.5	--	--	6.7	6.7
DAF Effl	0.70	1.20	0.030	0.029	6.8	6.7
DAF Filt	0.05	0.04	0.024	0.023	6.8	6.7

Note: All values represent averages of four measurements.

DOC results versus sample location for runs #13 and #14 are presented in Figure 4.10 as both fraction of raw water DOC and absolute DOC values. Values represent averages of two samples taken throughout a run. Absolute DOC values after pre-ozonation, flotation, and filtration are very similar for both runs. The raw water DOC was slightly higher during run #14 (8 minutes) resulting in slightly higher percent removals across treatment during run #14. With 8 minutes of flocculation time, flotation removed 45 percent of the raw water DOC and filtration following flotation removed 55 percent. With 16 minutes of flocculation time, flotation removed 39 percent of raw water DOC and subsequent filtration removed an additional 11 percent.

Particle counts across treatment were measured three times throughout each run. Average total particle counts, particle number average diameters and particle volume average diameters for runs #13 and #14 are presented in Table 4.15. The number distribution functions versus particle diameter for both runs are presented in Figure 4.11 and the volume distribution functions versus particle diameter for both runs are presented in Figure 4.12. The shorter flocculation time resulted in more numerous, smaller floc particles. With 16 minutes of flocculation time, total particle counts after flocculation were 2356 /mL with a number average diameter of 5.7μm. With 8 minutes of flocculation time, total particle counts after flocculation were 3541 /mL with a number average diameter of 4.9 μm. For particles smaller than 6 μm in diameter, examination of the number distribution function shows more numerous particles after flocculation for the 8 minute flocculation time compared to the 16 minute flocculation time. For particles larger than 50 μm in diameter,

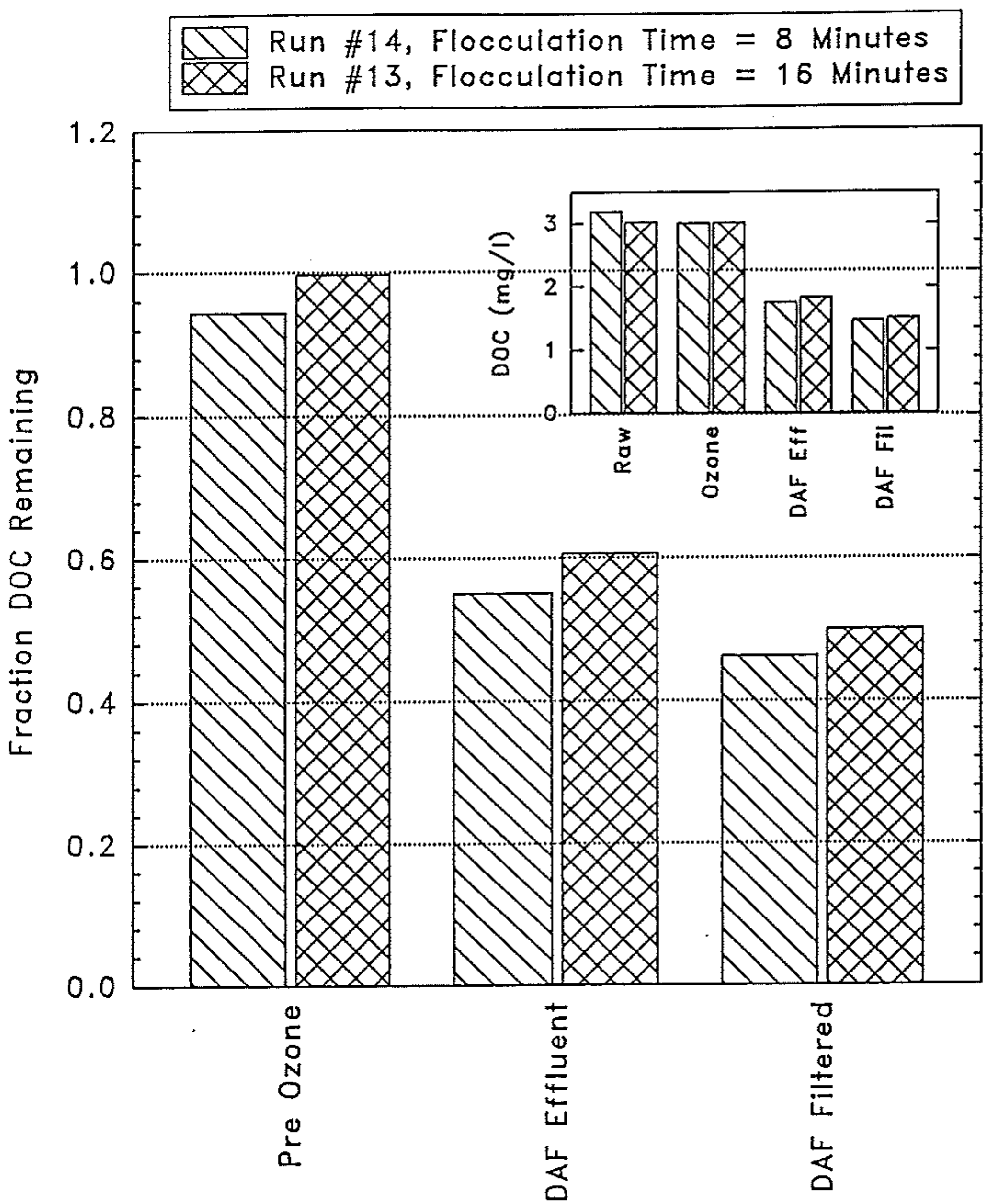


Figure 4.10 DOC Results for Runs #13 and #14

Table 4.15 **Particle Counts Across Treatment; Run #13, Flocculation Time=16 Minutes; Run #14, Flocculation Time=8 Minutes**

Location	Total Particles (#/mL)		Number Average Diameter (μm)		Volume Average Diameter (μm)	
	Run #13	Run #14	Run #13	Run#14	Run #13	Run #14
Raw Water	4172	3570	4.1	4.2	7.0	7.7
Ozone-Pre	3993	3615	4.0	4.2	7.2	7.8
Floc	2356	3541	5.7	4.9	13.7	11.0
DAF Effl	704	1528	3.7	3.8	6.0	6.0
DAF Filt	33	32	4.1	4.5	8.2	9.8

Note: All values represent averages of three measurements.

examination of the volume distribution function shows increased particle number and particle volume after flocculation for the 16 minute flocculation time compared to the 8 minute flocculation time.

After flotation, total particle counts were 704 /mL for 16 minutes flocculation time and 1528 /mL for 8 minutes flocculation time, with no significant difference in average particle size (number average diameter of 3.7 μm for both conditions). Examination of the number and volume distribution functions shows that for particles smaller than 10 μm in diameter, particle removal by flotation decreased as particle size decreased. The 8 minute flocculation period, which resulted in higher particle counts of small particles after flocculation, also resulted in higher particle counts of small particles after flotation. For particles larger than 10 μm in diameter, DAF effectively removed a large percentage of particles for both flocculation conditions.

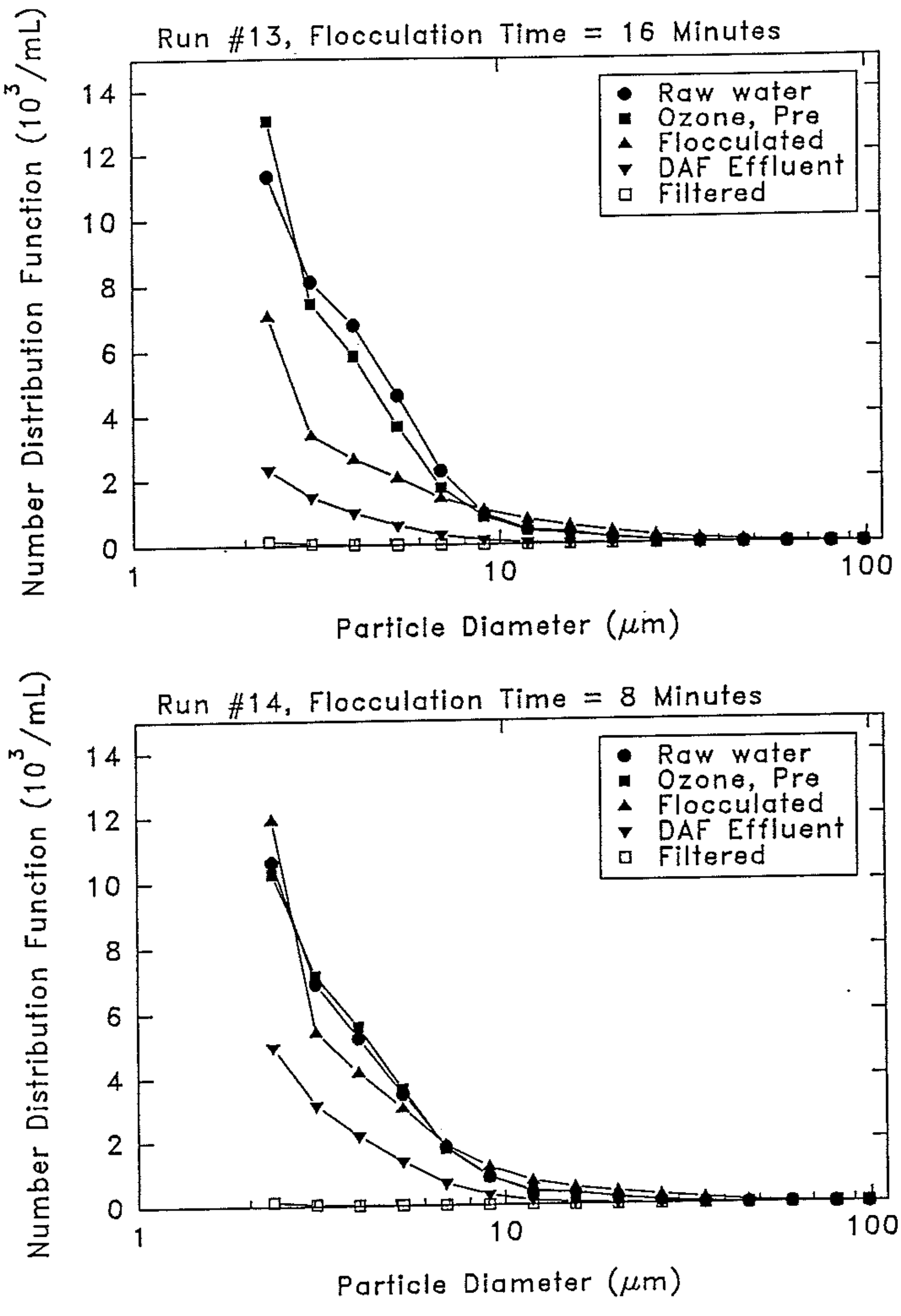


Figure 4.11 **Number Distribution Function versus Particle Diameter; Run #13, Flocculation Time=16 Minutes; Run #14, Flocculation Time=8 Minutes**

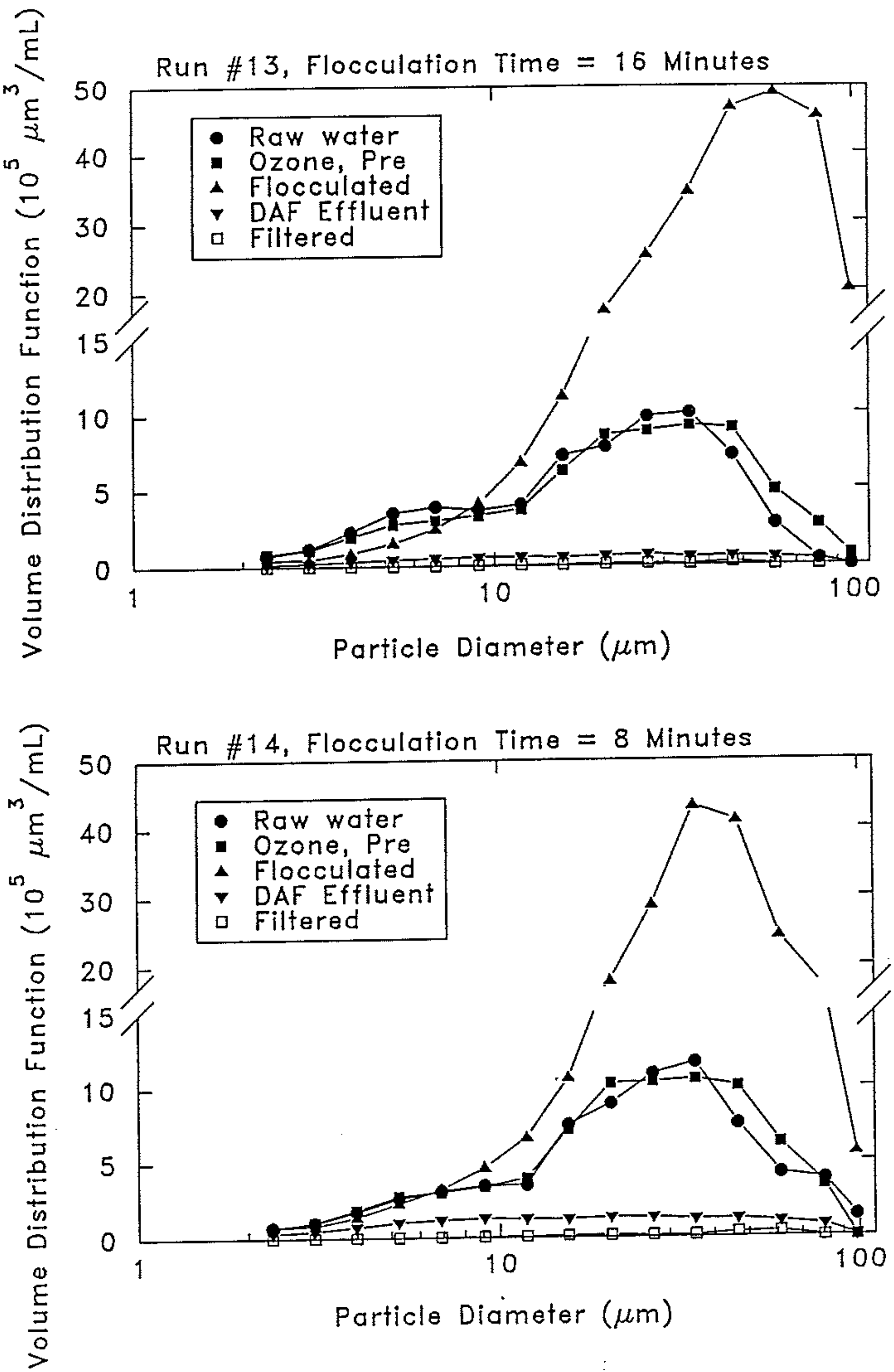


Figure 4.12 Volume Distribution Function Versus Particle Diameter; Run #13, Flocculation Time=16 Minutes; Run #14, Flocculation Time=8 Minutes

Particle counts of larger particles were similar for both conditions but slightly higher for the 8 minute flocculation period.

There were no significant differences in filtered water quality between the two flocculation conditions as measured by filtered water total particle counts of 33 /mL and 32 /mL for 16 and 8 minutes of flocculation time respectively.

4.1.5.2 Flocculation Time: Pilot Runs #19 and #20

Pilot runs #19 and #20 evaluated flocculation times of 16 and 8 minutes respectively with a filter hydraulic loading rate of 4.5 gpm/ft^2. Run #19 was conducted from October 24-25, 1992 and run #20 was conducted on October 25, 1992. Table 4.16 contains operating conditions, dosages and raw water data for runs #19 and #20. Ozonation and caustic application were not in use during these runs. Examination of the raw water data shows similar raw water quality for both runs.

Figure 4.13 presents results for runs #19 and #20 in terms of filtered water turbidity and UV254 and filter headloss versus run time. Steady state for both conditions was achieved approximately one hour after filter backwash. Filtered water turbidity and UV results for both flocculation conditions were similar to runs #13 and #14. Both flocculation conditions resulted in effective treatment. The average filtered water turbidity was 0.05 ntu with 16 minutes of flocculation and 0.03 ntu with 8 minutes of flocculation. The average filtered water UV254 removal was 75 percent and 76 percent with 16 and 8 minutes of flocculation time respectively. Headloss development was slightly higher with 8 minutes of flocculation time (1.0 in/hr and 1.4 in/hr for 16 and 8 minutes respectively). This is contrary to the results observed

Table 4.16 Operating Conditions, Dosages, and Raw Water Data; Run #19, Flocculation Time=16 Minutes; Run #20, Flocculation Time=8 Minutes

Parameter	Run #19 (10/24/92)	Run #20 (10/25/92)
Operating Conditions		
Recycle Ratio (%)	8.0	8.0
Sludge Removal Freq. (1/# hr)	1 / 3 hrs	1 / 3 hrs
Filter Loading (gpm/ft^2)	4.5	4.5
Flocculation Time (min)	16	8
Chemical and Ozone Dosages		
Ferric Chloride (mg/L)	7.6	7.6
Polymer (mg/L)	2.0	2.0
Caustic (mg/L)	0.0	0.0
Ozone (mg/L)	Off	Off
Raw Water Characteristics		
Turbidity (ntu)	1.53 (1.48-1.65)	1.65 (1.55-1.75)
UV254 (cm^{-1})	0.105 (0.102-0.108)	0.105 (0.103-0.106)
pH	6.8 (6.8-6.9)	6.9 (6.8-7.0)

during runs #13 and #14 where 8 minutes of flocculation resulted in lower headloss development than for 16 minutes.

Average turbidity, UV254 and pH through treatment for runs #19 and #20 are presented in Table 4.17. The numbers are averages of four measurements taken throughout each run. Turbidity, UV254 and pH results from runs #19 and #20 are similar to resulted presented from runs #13 and #14. The DAF effluent turbidity was higher for the 8 minute flocculation condition (0.98 ntu) than the 16 minute

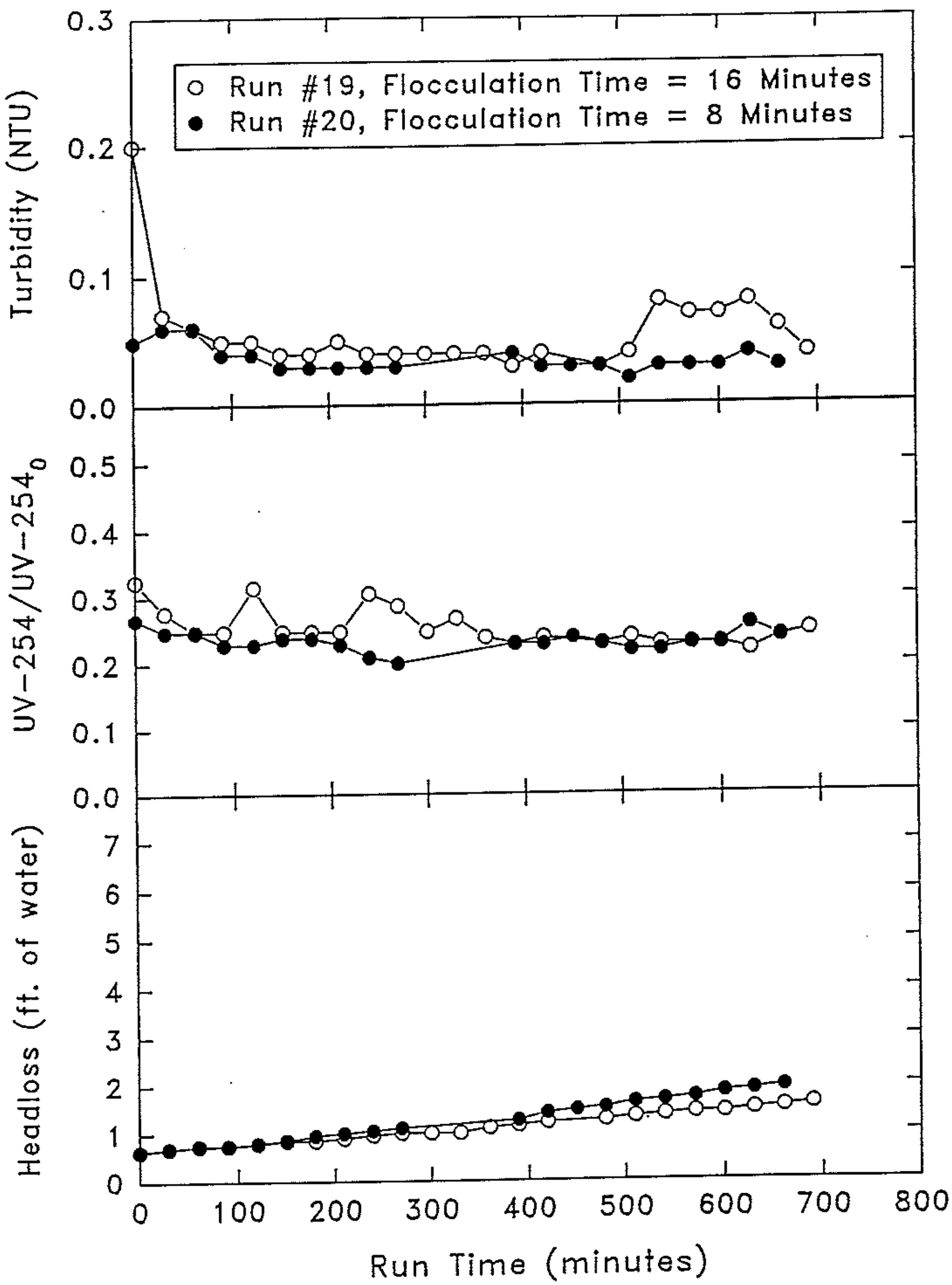


Figure 4.13 **Filtered Water Quality; Run #19, Flocculation Time=16 Minutes; Run #20, Flocculation Time=8 Minutes**

Table 4.17 **Turbidity, UV254 and pH Across Treatment; Run #19, Flocculation Time=16 Minutes; Run #20, Flocculation Time=8 Minutes**

Location	Turbidity (ntu)		UV254 (cm^{-1})		pH	
	Run #19	Run #20	Run #19	Run #20	Run #19	Run #20
Raw Water	1.53	1.65	0.105	0.105	6.8	6.9
Ozone-Pre	Off	Off	Off	Off	Off	Off
Floc	2.9	3.7	--	--	6.5	6.8
DAF Effl	0.68	0.89	0.030	0.028	6.5	6.6
DAF Filt	0.05	0.04	0.028	0.025	6.5	6.7

Note: All values represent averages of four measurements.

flocculation condition (0.68 ntu). The average turbidity after flocculation was 2.9 ntu with 16 minutes of flocculation and 3.7 ntu with 8 minutes.

Results of DOC analysis on samples collected across treatment for runs #19 and #20 are presented in Figure 4.14. Values represent averages of two samples taken throughout a run. DOC results across treatment are similar for the two flocculation times. After flotation, DOC removals were 48 percent with an 8 minute flocculation period and 45 percent with a 16 minute flocculation period. After filtration, DOC removals were 52 percent with an 8 minute flocculation period and 55 percent with a 16 minute flocculation period.

Particle counts were measured two times across treatment for runs #19 and #20. Average total particle counts, particle number average diameter and particle volume average diameter for both runs are reported in Table 4.18. The number

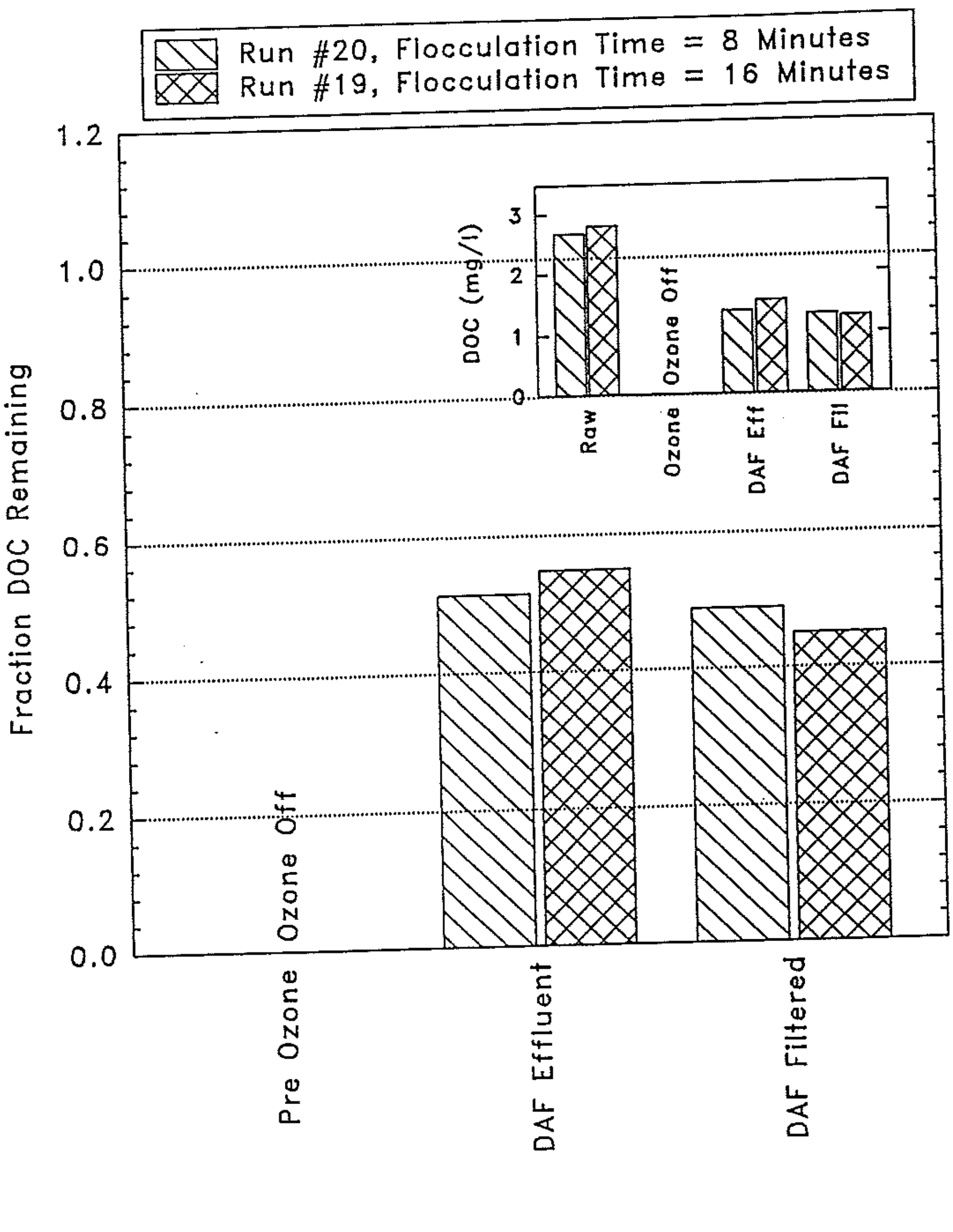


Figure 4.14 DOC Results for Runs #19 and #20

Table 4.18 Particle Counts Across Treatment; Run #19, Flocculation Time=16 Minutes; Run #20, Flocculation Time=8 Minutes

Location	Total Particles (#/mL)		Number Average Diameter (μm)		Volume Average Diameter (μm)	
	Run #19	Run #20	Run #19	Run#20	Run #19	Run #20
Raw Water	10884	15000	3.4	3.4	4.7	4.6
Ozone-Pre	Off	Off	Off	Off	Off	Off
Floc	4483	9001	7.9	6.5	12.5	9.6
DAF Effl	829	1786	3.6	3.6	5.7	5.0
DAF Filt	40	98	4.7	4.9	8.7	9.2

Note: All values represent averages of three measurements.

distribution and volume distribution functions versus particle diameter are presented in Figure 4.15 and Figure 4.16 respectively. During runs #19 and #20, raw water and flocculated samples for particle analysis were diluted with filtered water. Dilution results in more accurate and higher counts when total particles in the sample are above the coincidence limit of the sensor.

Overall trends in particle counts during runs #19 and #20 were similar to results from runs #13 and #14. The shorter flocculation time produced more numerous flocculated particles smaller than 10 μm in diameter and fewer flocculated particles larger than 10 μm in diameter. Total particle counts after 16 minutes of flocculation (flocculated sample) were 4483 /mL with an average number diameter of 7.9 μm; with 8 minutes of flocculation, total particle counts were 9001 /mL after flocculation with an average number diameter of 6.5 μm.

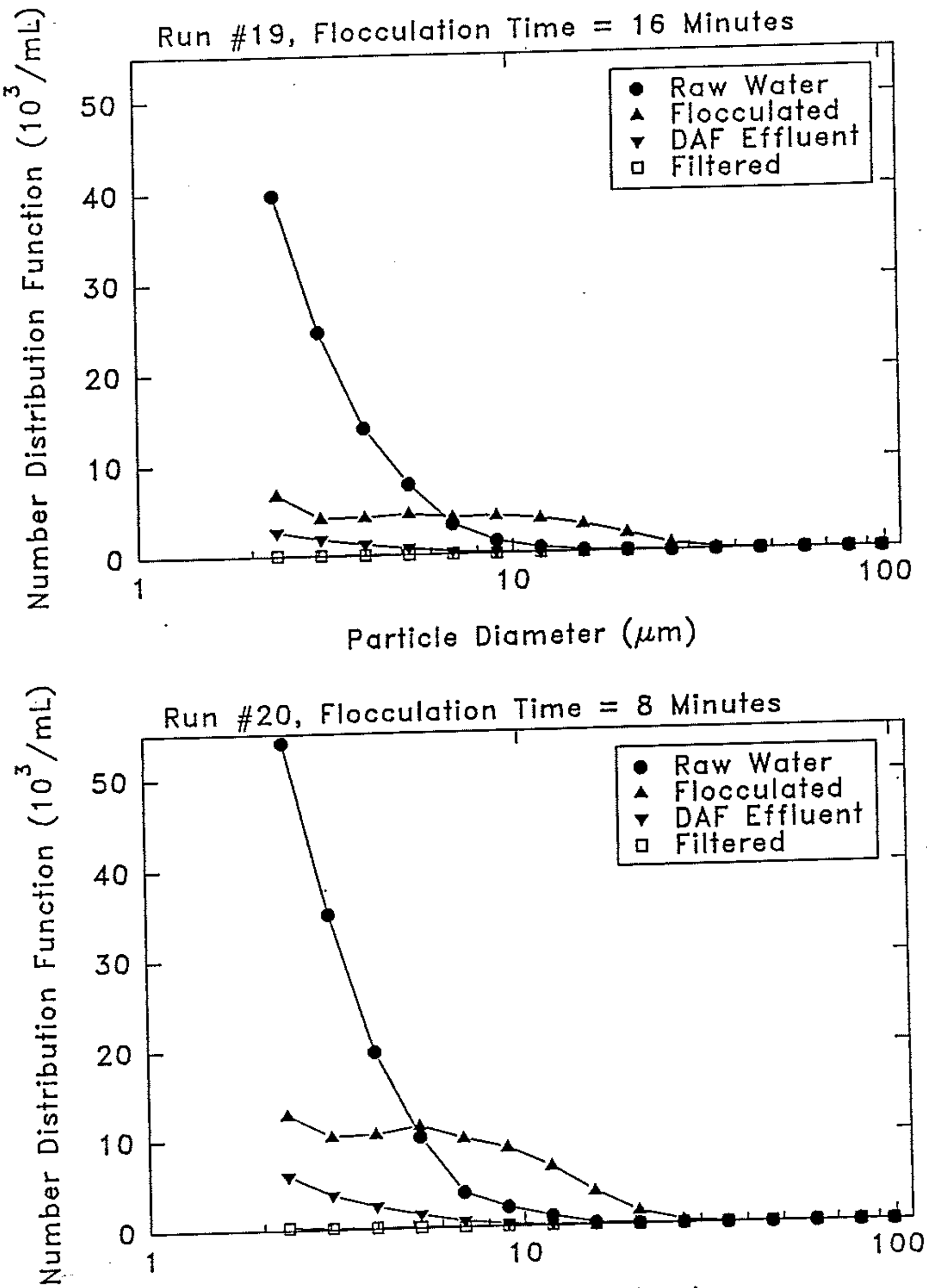


Figure 4.15 Number Distribution Function Versus Particle Diameter; Run #19, Flocculation Time=16 Minutes; Run #20, Flocculation Time=8 Minutes

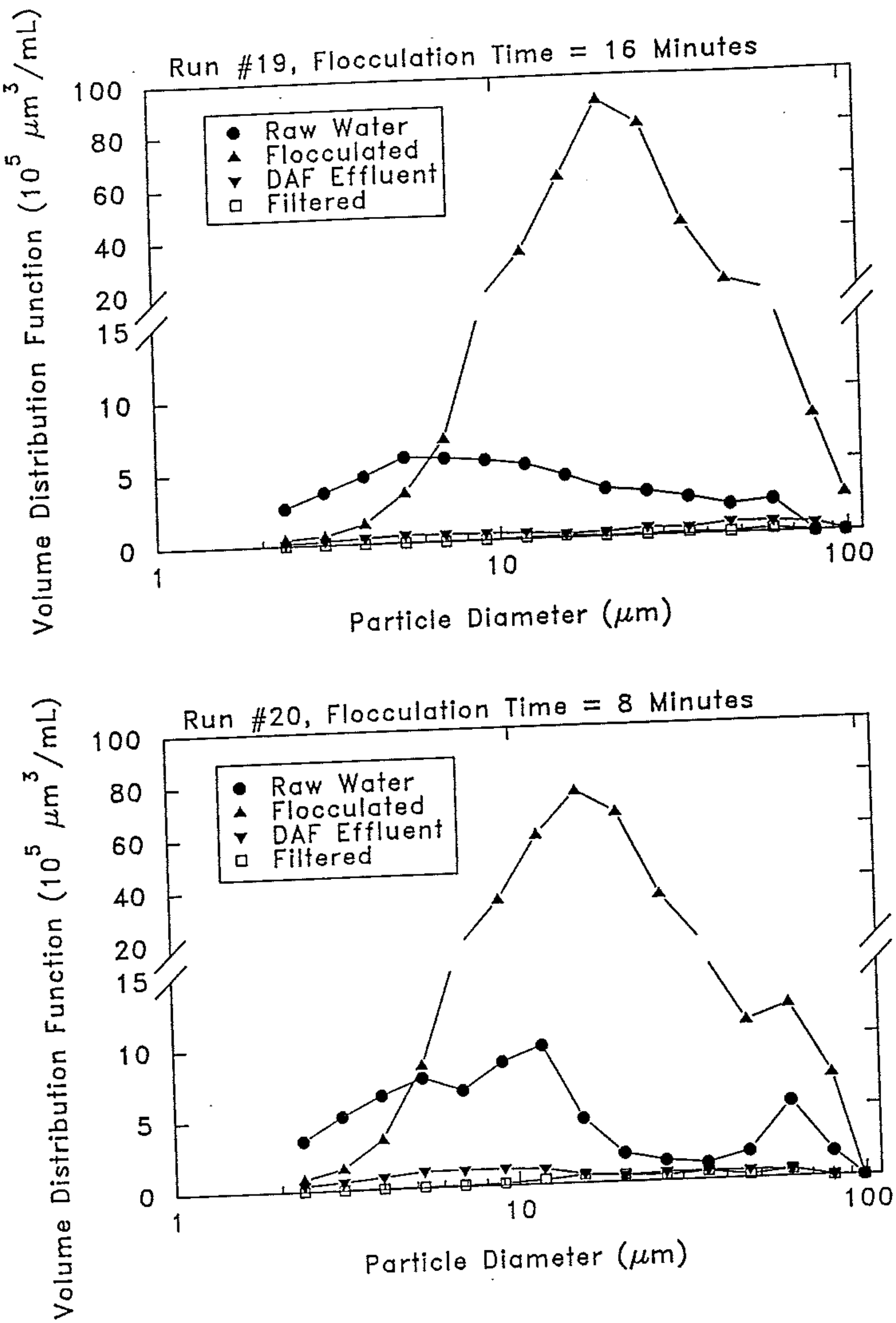


Figure 4.16 **Volume Distribution Function Versus Particle Diameter; Run #19, Flocculation Time=16 Minutes; Run #20, Flocculation Time=8 Minutes**

Total particle counts after flotation were higher for the 8 minute flocculation time than for the 16 minute flocculation time (1786 vs 829 /mL). After flotation, the number average diameter was 3.6 μm for both flocculation conditions. Examination of the number and volume distribution functions shows that particle removal by DAF generally decreased as particle diameter decreased (particularly for the smallest particles measured). Overall particulate removal was effective for both flocculation conditions with the 8 minute flocculation period resulting in slightly higher particle counts of all size particles after flotation.

After filtration, the total particle counts were slightly higher for the 8 minute flocculation condition than the 16 minute flocculation condition (98 vs 40 #/mL).

4.1.5.3. Flocculation Time: Pilot Runs #16 and #17

Pilot runs #16 and #17 evaluated flocculation times of 8 and 16 minutes respectively with a filter hydraulic loading rate of 4.5 gpm/ft^2. Run #16 was conducted on August 12, 1992 and run #17 was conducted on August 13, 1992. Table 4.19 contains operating conditions, dosages and raw water data for runs #16 and #17. The raw water intake to the full scale plant and therefore the pilot trains was changed between runs #16 and #17 resulting in higher measured values of raw water turbidity (1.8 ntu versus 1.2 ntu) and UV254 (0.14 cm^{-1} versus 0.12 cm^{-1}) for run #16. Microscopic observation of algae by SCCRWA personnel suggested higher raw water algae levels during run #17 than for run #16.

Figure 4.17 presents filtered water turbidity, fraction of raw water UV254 and filter headloss development versus run time for runs #13 and #14. Overall treatment by DAF was effective at both flocculation times. Average filtered water turbidity was

Table 4.19 Operating Conditions, Dosages, and Raw Water Data; Run #16, Flocculation Time=8 Minutes; Run #17, Flocculation Time=16 Minutes

Parameter	Run #16 (8/12/92)	Run #17 (8/13/92)
Operating Conditions		
Recycle Ratio (%)	8.0	8.0
Sludge Removal Freq. (1/# hr)	1 / 3 hrs	1 / 3 hrs
Filter Loading (gpm/ft^2)	4.5	4.5
Flocculation Time (min)	8	16
Chemical and Ozone Dosages		
Ferric Chloride (mg/L)	10.2	9.8
Polymer (mg/L)	2.8	2.8
Caustic (mg/L)	3.6	4.4
Ozone (mg/L)	1.5-Pre	1.5-Pre
Raw Water Characteristics		
Turbidity (ntu)	1.76 (1.58-2.00)	1.22 (1.11-1.39)
UV254 (cm^{-1})	0.139 (0.134-0.142)	0.120 (0.118-0.123)
pH	6.7 (6.7-6.8)	6.6 (6.6-6.6)

0.06 ntu with 8 minutes of flocculation time (run #16) and 0.01 ntu with 16 minutes of flocculation time (run #17). The slightly improved finished water quality on the DAF train during run #16 compared to run #17 was mirrored on the parallel direct filtration train (not shown), which produced a filtered water turbidity of 0.04 ntu during run #16 and 0.02 ntu during run #17. The filtered water UV254 values were slightly higher with 8 minutes of flocculation time than with 16 minutes of flocculation time (0.021 cm^{-1} versus 0.019 cm^{-1}), but when normalized as percent

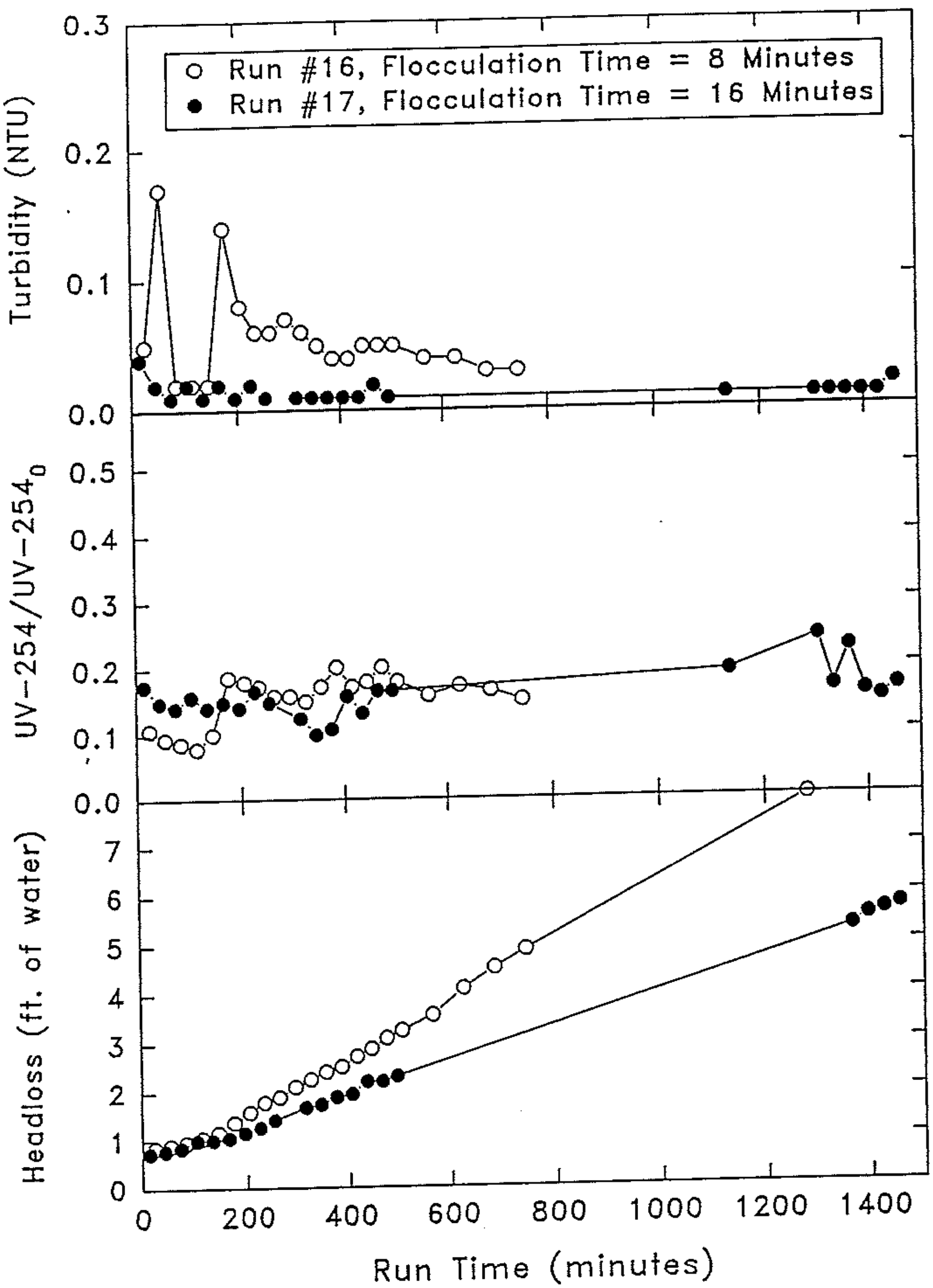


Figure 4.17 Filtered Water Quality; Run #16, Flocculation Time=8 Minutes; Run #17, Flocculation Time=16 Minutes

removals, 8 minutes of flocculation time resulted in slightly more effective UV254 removal than 16 minutes of flocculation time (14 percent of raw water versus 16 percent). Filter headloss increased at a higher rate with 8 minutes of flocculation time (4.1 in/hr) than with 16 minutes of flocculation time (2.5 in/hr). The headloss development rates for the parallel DF train during runs #16 and #17 were similar to each other while higher than for the DAF train (5.8 and 6.2 in/hr respectively).

Average steady state turbidity, UV254 and pH values across treatment for each run are presented in Table 4.20. The values are averages of three samples taken

Table 4.20 Turbidity, UV254 and pH Across Treatment; Run #16, Flocculation Time=8 Minutes; Run #17, Flocculation Time=16 Minutes

Location	Turbidity (ntu)		UV254 (cm^{-1})		pH	
	Run #16	Run #17	Run #16	Run #17	Run #16	Run #17
Raw Water	1.76	1.22	0.139	0.120	6.7	6.6
Ozone-Pre	1.69	1.19	0.115	0.095	6.8	6.6
Floc	3.5	2.5	--	--	6.7	6.5
DAF Effl	1.42	0.46	0.028	0.024	6.7	6.6
DAF Filt	0.08	0.01	0.023	0.017	6.6	6.5

Note: All values represent averages of three measurements.

throughout each run. As discussed previously, differences between runs #16 and #17 are difficult to analyze due to the change in raw water quality between the two runs. With a flocculation time of 8 minutes, the turbidity after flocculation was 3.5 ntu and 1.42 ntu after flotation. While the turbidity after flotation with 8 minutes of flocculation time was high, a value of 1.42 ntu still represents acceptable treatment by flotation.

Results of DOC analysis on samples collected across treatment for runs #16 and #17 are presented in Figure 4.18. DOC samples were taken one time during run #16 and two times during run #17. The raw water DOC was higher during run #16 (8 minute flocculation time) than during run #17 (4.1 mg/L versus 3.3 mg/L). Removal of DOC through treatment was effective during both runs. With 8 minutes of flocculation time, flotation removed 51 percent of the raw water DOC and filtration removed an additional 11 percent. With 16 minutes of flocculation time, flotation removed 46 percent of the raw water DOC and filtration removed an additional 6 percent.

Particle counts were not measured during run #16 nor during run #17 due to a mechanical failure of the particle counter.

4.1.5.4 Discussion

Eight minutes of flocculation time prior to filtration resulted in effective overall treatment of West River source water during run #14 with a filter hydraulic loading of 3.0 gpm/ft^2 and during runs #16 and #20 with a filter hydraulic loading of 4.5 gpm/ft^2. Finished water quality with an 8 minute flocculation period (runs #14 and #20) was similar to finished water quality with a 16 minute flocculation period (runs #13 and #19).

Particle count data for runs #13, 14, 19 and 20 show that the 8 minute flocculation condition resulted in smaller, more numerous particles after flocculation than the 16 minute flocculation condition. In general, the number of particles smaller

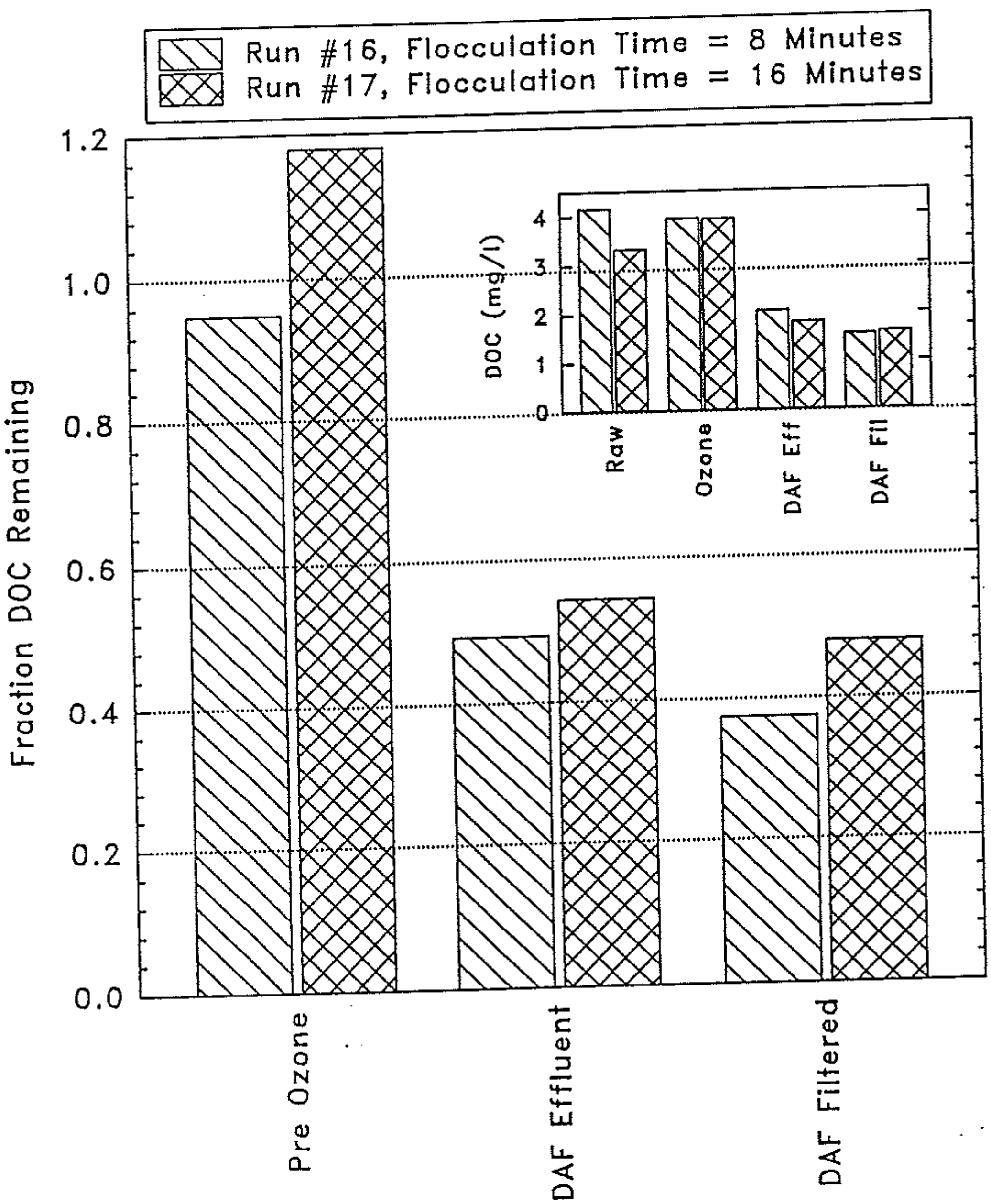


Figure 4.18 DOC Results for Runs #16 and #17

than 10 μm after flocculation was higher for the 8 minute flocculation condition and the number of particles larger than 10 μm after flocculation was lower for the 8 minute flocculation condition. The differences in flocculated particle size between the two flocculation conditions is attributed to the shorter total detention time and the fact that the 8 minute condition had only one stage of flocculation and the 16 minute condition had two stages of flocculation.

The differences in flocculated particles resulted in slightly increased turbidity and particle counts after flotation for the 8 minute flocculation condition than the 16 minute flocculation condition. Sixteen and eight minutes of flocculation time resulted in clarified water turbidities of 0.70 ntu and 1.2 ntu respectively for runs #13 and #14, 0.68 ntu and 0.89 ntu respectively for runs #19 and #20, and 0.46 ntu and 1.42 ntu respectively for runs #17 and #16. Total particle counts of the clarified sample with 8 minutes of flocculation time were twice the particle counts with 16 minutes of flocculation time.

The increased turbidity and particle counts after flotation for the 8 minute flocculation time represent an increased particle loading to the filters. With an increase in the particle number applied to the filters, for the same size particle or for smaller particles, the rate of filter headloss development is expected to increase (Tobiason *et al.* (1993b)). The increased particle loading to the filters for the 8 minute flocculation condition resulted in increased filter headloss development when comparing runs #16 and #17 and runs #19 and #20 but unexpectedly resulted in decreased filter headloss development with 8 minutes of flocculation when comparing runs #13 and #14.

The particle count results generally agree with the model presented previously by Edzwald and co-workers that predicts: for particles above 1 μm in diameter, particle removal by DAF decreases as particle diameter decreases.

The results are consistent with the work of Edzwald and co-workers, who found that flocculation times as low as 5 minutes resulted in effective flotation. The results also agree with the work of Kaminski *et al.* (1991), Walsh (1991), Edzwald (1993); Edzwald and Walsh (1992); and Edzwald *et al.* (1992), which reported effective treatment of Lake Whitney water with flocculation times as low as 8 minutes. Bunker (1993) also reported effective flotation on West River source water with a 5 minute flocculation period. The results differ slightly from work by Zabel (1984; 1985) who suggested 12-20 minutes of flocculation for effective flotation.

4.1.6 Effects of Ozone

Ozone was applied either before flotation (pre-ozonation), after flotation (intermediate-ozonation) or not at all throughout the study. Results are presented below from multiple runs designed to evaluate the effects of pre- and intermediate-ozonation on flotation and filtration performance. Intermediate ozonation began on May 30, 1992. This configuration allowed for lower ozone demand than for pre-ozonation and less possibility for the creation of ozone by-products. Runs #1 and #2, performed on June 22 and 23, 1992 respectively, compared treatment with intermediate-ozonation (run #1) to treatment without intermediate ozonation (run #2) in conjunction with ferric chloride with polymer coagulation conditions. Runs #4 and #5, performed on June 24 and 25, 1992 respectively, compared intermediate-ozonation (run #5) to no ozonation (run #4) except the only primary coagulant was ferric chloride alone.

Treatment with intermediate ozonation resulted in unacceptable turbidity levels in the filtered water during run #5 and the beginning of run #6 and was discontinued on July 2, 1992. Pre-ozonation began on July 8 and was continued through most of the remainder of the study. The effects of pre-ozonation were evaluated during run #15, performed on August 11, 1992, and run #18, performed on October 23-24, 1992. During runs #15 and #18, pre-ozonation was discontinued after four or five hours of data collection; the no ozone condition was evaluated for an additional 5-8 hours.

The gas transfer efficiency of the ozone contactor (transfer efficiency) and the concentration of ozone after ozonation (wet residual) were measured two to three times per week to evaluate contactor performance and ozone demand. The transfer efficiency is computed from measurements of the mass concentration of ozone in the applied and exit gases on the contactor ((applied gas - off gas) / applied gas x 100%). For the intermediate ozonation condition at 1.0 mg/L of applied ozone, the transfer efficiency typically ranged from 74 to 83 percent and the wet residual typically ranged from 0.10 to 0.20 mg/L of ozone. For the pre-ozonation condition at 1.5 mg/L of applied ozone, the transfer efficiency typically ranged from 72 to 82 percent and the wet residual typically ranged from 0.02 to 0.07 mg/L of ozone.

4.1.6.1 Intermediate Ozone vs No Ozone: Run #1 vs #2

Run #1 was performed on June 22, 1992 with application of 1.0 mg/L of ozone after flotation. Run #2 was performed on June 23, 1992 with no ozone applied to the DAF pilot train. Results from runs #1 and #2 are presented below. Operating conditions of the pilot plant during runs #1 and #2 are presented in Table 4.21. The

Table 4.21 Operating Conditions, Dosages, and Raw Water Data; Run #1, Intermediate-Ozonation; Run #2, No Ozonation

Parameter	Run #1 (6/22/92)	Run #2 (6/23/92)
Operating Conditions		
Recycle Ratio (%)	8.0	8.0
Sludge Removal Freq. (1/# hr)	1 / 1 hr	1 / 1 hr
Filter Loading (gpm/ft^2)	3.0	3.0
Flocculation Time (min)	16	16
Chemical and Ozone Dosages		
Ferric Chloride (mg/L)	8.9	8.8
Polymer (mg/L)	3.4	2.8
Caustic (mg/L)	5.8	5.8
Ozone (mg/L)	1.0-Int	Off
Raw Water Characteristics		
Turbidity (ntu)	1.06 (0.88-1.46)	0.95 (0.83-1.15)
UV254 (cm^{-1})	0.106 (0.103-0.111)	0.103 (0.100-0.105)
pH	6.7 (6.6-6.7)	6.9 (6.9-6.9)

pilot plant configuration and coagulation conditions were constant between the two runs except for ozonation conditions. The raw water quality was similar for both runs as measured by turbidity, UV254 and pH.

DAF train filtered water turbidity and UV254 and filter headloss data collected during runs #1 and #2 are presented in Figure 4.19. Filtered water turbidity was

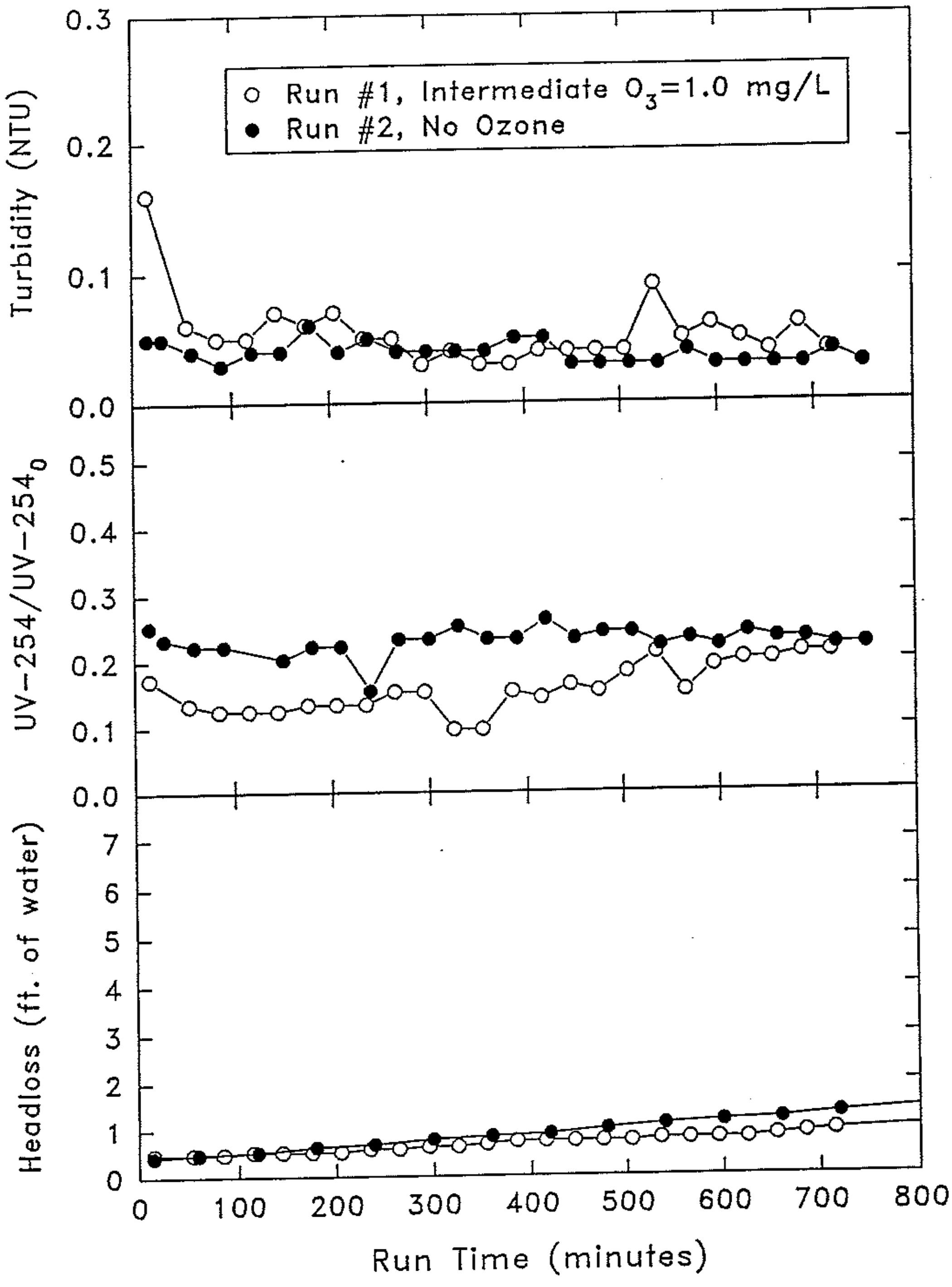


Figure 4.19 Filtered Water Quality; Run #1, Intermediate-Ozonation; Run #2, No Ozonation

consistently below 0.08 ntu during both runs. Intermediate-ozonation (run #1) resulted in greater overall UV254 removal (average of 85 percent) than no ozonation (average of 77 percent). Both conditions resulted in very reasonable filter headloss development but headloss development was slightly lower when ozone was applied after flotation (0.6 in/hr over 22 hours) than when no ozone was applied (0.9 in/hr over 23 hours).

Turbidity, UV254 and pH data measured at various locations along the DAF train are presented in Table 4.22. Examination of Table 4.22 shows that treatment

Table 4.22 Turbidity, UV254 and pH Across Treatment; Run #1, Intermediate-Ozonation; Run #2, No Ozonation

Location	Turbidity (ntu)		UV254 (cm^{-1})		pH	
	Run #1	Run #2	Run #1	Run#2	Run #1	Run #2
Raw Water	1.06	0.95	0.106	0.103	6.7	6.9
Floc	1.3	1.3	--	--	6.6	6.7
DAF Effl	0.55	0.60	0.033	0.027	6.6	6.9
Ozone-Int	0.57	Off	0.021	Off	6.7	Off
DAF Filt	0.05	0.04	0.016	0.023	6.6	6.9

Note: Run #1 values represent averages of four measurements.
Run #2 values represent averages of three measurements.

was similar for both runs through coagulation, flocculation and flotation with the exception of slightly higher UV254 values after flotation for run #2 (no-ozonation) than run #1 (intermediate-ozonation) (0.033 cm^{-1} vs 0.027 cm^{-1}). Ozonation of the clarified water reduced the average UV254 from 0.033 cm^{-1} after flotation to 0.021 cm^{-1} after ozonation. The direct reduction of UV254 by intermediate ozonation resulted in the secondary effect of UV254 reduction through filtration as discussed in the previous paragraph.

DOC results from runs #1 and #2 are presented in Figure 4.20 in terms of absolute DOC and percent of raw water DOC across treatment. Values represent averages of samples taken twice throughout each run. Intermediate ozonation had no significant effects on overall removal of DOC through the filters (53 percent for the intermediate ozonation condition and 51 percent for the no ozone condition). Results from run #1 showed an increase from 1.3 mg/L DOC after clarification to 1.4 mg/L after intermediation ozonation.

Particle count results from runs #1 and #2 are presented in Table 4.23 in terms of total particle counts, number average diameter and volume average diameter across treatment. Values represent averages of two samples. Intermediate ozonation increased the total particle counts from 754 /mL after flotation to 1538 /mL after ozonation, while the average number particle diameter decreased from 3.9 μm after flotation to 3.5 μm after ozonation. Intermediate ozonation had no negative impact on particle removal by subsequent filtration as measured by filtered water total particle counts of 9 /mL for the intermediate ozonation condition (run #1) and 60 /mL for the no ozone condition (run #2).

4.1.6.2 Intermediate Ozone vs No Ozone: Run #5 vs #4

Pilot run #4, conducted on June 25, 1992, acted as a control run (no ozone) for run #5 which was performed on June 26, 1992 with 1.0 mg/L of ozone applied after flotation. Runs #4 and #5 differ from runs #1 and #2 in that ferric chloride and polymer were utilized in runs #1 and #2 and ferric chloride alone was utilized in runs

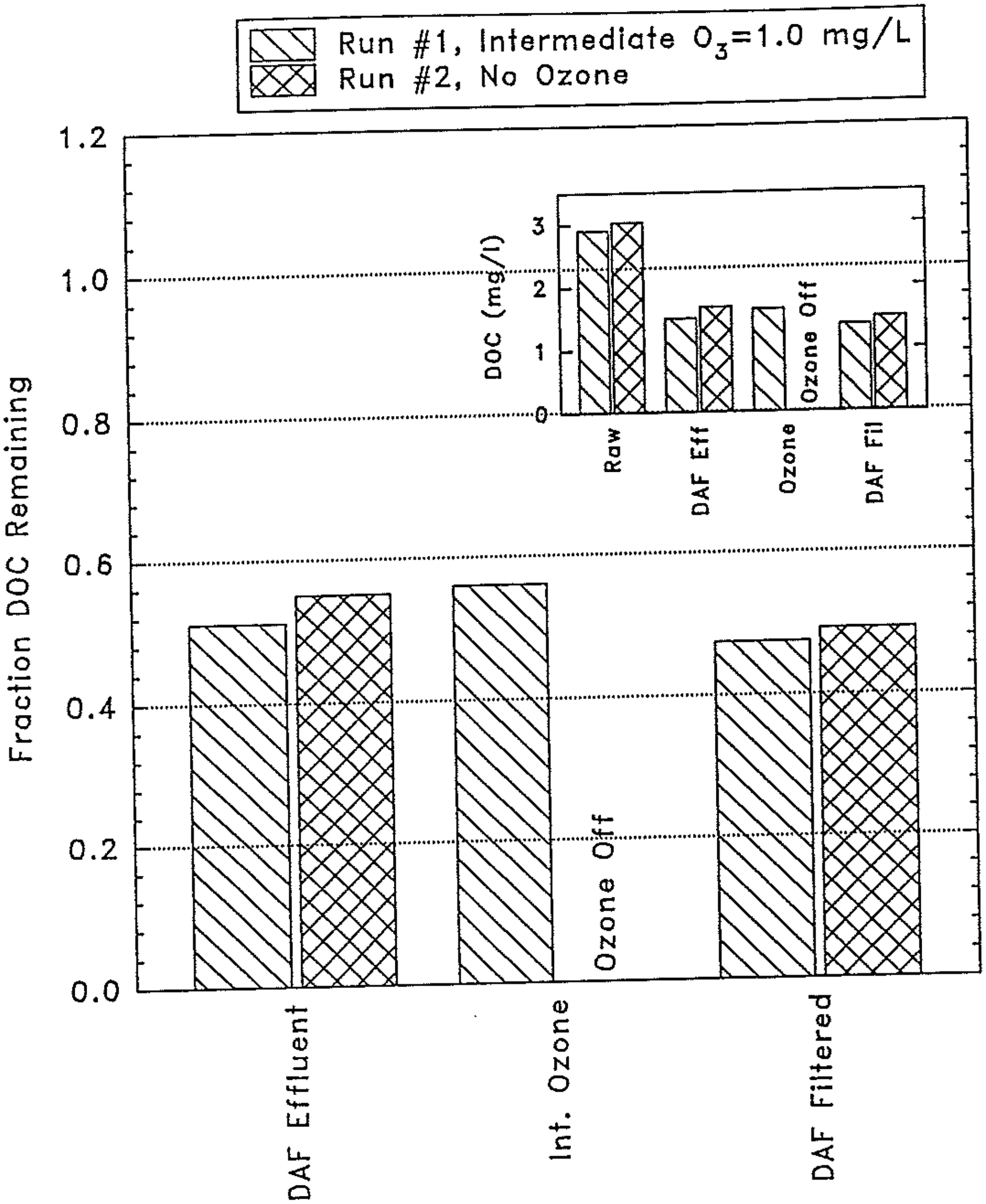


Figure 4.20 DOC Results for Runs #1 and #2

Table 4.23 **Particle Counts Across Treatment; Run #1, Intermediate-Ozonation; Run #2, No Ozonation**

Location	Total Particles (#/mL)		Number Average Diameter (μm)		Volume Average Diameter (μm)	
	Run #1	Run #2	Run #1	Run#2	Run #1	Run #2
Raw Water	4747	3980	4.3	4.4	7.0	7.7
Floc	1914	1965	5.1	5.3	11.5	12.3
DAF Effl	754	659	3.9	4.1	7.2	8.5
Ozone-Int	1538	Off	3.5	Off	6.7	Off
DAF Filt	9	60	4.6	4.7	9.3	9.1

#4 and #5. Operating conditions, coagulation dosages and raw water data (one measurement) for runs #4 and #5 are presented in Table 4.24.

Results from run #4 and #5 are presented in Figure 4.21 as filtered water turbidity and UV254 and filter headloss development. Run #5 (intermediate ozonation) was unsuccessful due to filtered water turbidities between 0.5 to 0.4 ntu for the first five hours after filter backwash. However, filtered water UV254 values averaged 86 percent removal of raw water UV. The run was terminated after 5 hours.

A limited number of samples across treatment were measured for turbidity and UV254 during run #5. Two hours into the run, the clarified turbidity was 0.56 ntu and the UV254 was 0.023 cm^{-1}. Intermediate ozonation increased the turbidity to 1.65 ntu and decreased the UV254 to 0.015 cm^{-1}. Subsequent filtration decreased the turbidity to 0.47 ntu and left the UV254 unchanged. Four hours into the run, the clarified, intermediate ozonation, and filtered water turbidities were 0.51 ntu, 1.85

Table 4.24 **Operating Conditions, Dosages, and Raw Water Data; Run #4, No Ozonation; Run #5, Intermediate-Ozonation**

Parameter	Run #4 (6/25/92)	Run #5 (6/26/92)
Operating Conditions		
Recycle Ratio (%)	8.0	8.0
Sludge Removal Freq. (1/# hr)	1 / 1 hr	1 / 1 hr
Filter Loading (gpm/ft^2)	3.0	3.0
Flocculation Time (min)	16	16
Chemical and Ozone Dosages		
Ferric Chloride (mg/L)	18.5	18.5
Polymer (mg/L)	0.0	0.0
Caustic (mg/L)	8.8	8.8
Ozone (mg/L)	Off	1.0 Int
Raw Water Characteristics		
Turbidity (ntu)	1.06 (0.88-1.46)	0.88
UV254 (cm^{-1})	0.106 (0.103-0.111)	0.105
pH	6.7 (6.6-6.7)	6.8

ntu, and 0.36 ntu respectively. DOC and particle data are not available for run #5.

Following run #5 and during the beginning of run #6 on July 2, 1992, the pilot plant was configured with intermediate ozonation (1.0 mg/L) with ferric chloride and polymer for coagulation. Run #6, which evaluated recycle ratio, was discussed in section 4.1.2. Results similar to those observed during run #5 were observed at the beginning of run #6 (see the first four hours of the run shown in Figure 4.5). With intermediate ozonation, filtered water turbidity was as high as 0.67 ntu. After

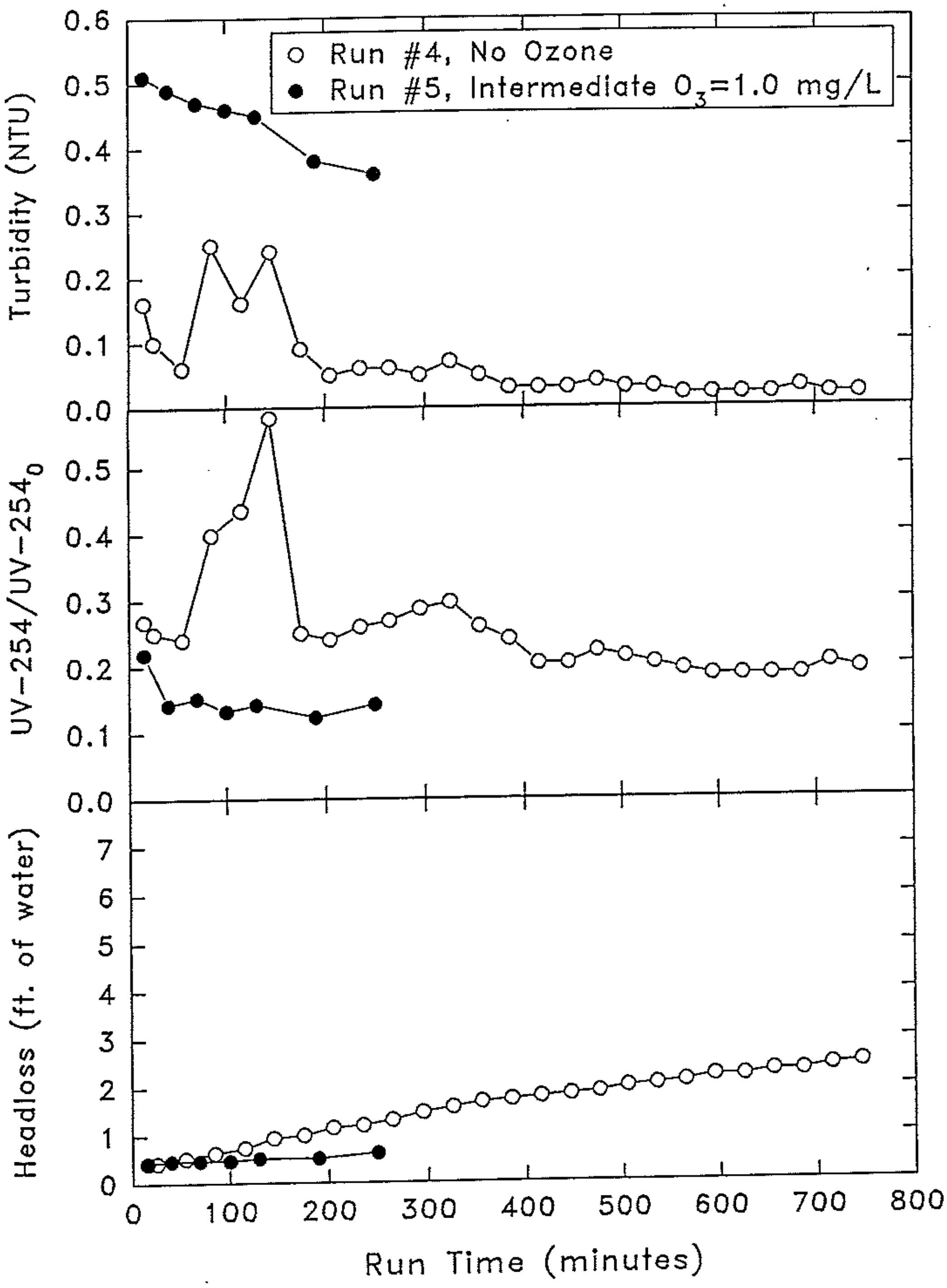


Figure 4.21 **Filtered Water Quality; Run #4, No Ozonation; Run #5, Intermediate-Ozonation**

intermediate ozonation was discontinued, the filtered water turbidity decreased to 0.02 ntu. Manganese data is not available for run #5. However, on July 2, 1992 (run #6), the raw water manganese level was 0.22 mg/L as measured by SCCRWA personnel.

Evaluating the limited data available, the most probable explanation for the high turbidity levels after ozonation and after filtration is oxidation and subsequent precipitation of manganese. Without further chemical addition, removal of the precipitate by filtration will be poor, resulting in increased turbidity levels. Another possible cause of high turbidity can be unfavorable coagulation conditions that result in stabilized particles. However, the effective removal of UV254 through treatment and effective removal of turbidity by flotation during run #5 suggest favorable coagulation conditions during the run.

4.1.6.3 Pre-Ozonation vs No Ozonation: Run # 15

The effects of pre-ozonation were evaluated during run #15 on August 11, 1992. Three ozone conditions were evaluated for approximately 4 hours each. First, pre-ozonation was applied at 1.5 mg/L (ozone condition); next, air from the ozone generation system without ozone was pumped into the ozone contactor (air only condition) and finally, neither air nor ozone were applied (no air/no ozone condition). The air only condition was evaluated to help distinguish between the chemical effects of ozone and the mechanical and turbulent effects of the gas application in the ozone contactor.

Operating conditions, coagulant dosages and raw water data from run #15 are presented in Table 4.25. The raw water was similar throughout the 12 hour run as

Table 4.25 Operating Conditions, Dosages, and Raw Water Data; Run #15, Evaluation of Pre-Ozonation

Parameter	Run #15 (8/11/92)
Operating Conditions	
Recycle Ratio (%)	8.0
Sludge Removal Freq. (1/# hr)	1 / 3 hrs
Filter Loading (gpm/ft^2)	3.0
Flocculation Time (min)	16
Chemical and Ozone Dosages	
Ferric Chloride (mg/L)	10.4
Polymer (mg/L)	3.4
Caustic (mg/L)	4.5
Ozone (mg/L)	1.5-Pre; Air Only; No Air/No Ozone
Raw Water Characteristics	
Turbidity (ntu)	1.61 (1.46-1.72)
UV254 (cm^{-1})	0.141 (0.138-0.144)
pH	6.7 (6.6-6.7)

measured by turbidity, UV254 and pH. The aqueous ozone residuals after ozonation in the DAF train were 0.07 mg/L and 0.08 mg/L for the two contactors respectively. Ozone transfer efficiency for the DAF ozone contactors was not available on August 11, 1992.

Filtered water turbidity and UV254, clarified water turbidity and filter headloss data versus run time for run #15 are presented in Figure 4.22. Steady state for each condition was reached after approximately one and one half hours. Evaluation of Figure 4.22 shows effective overall treatment regardless of ozone

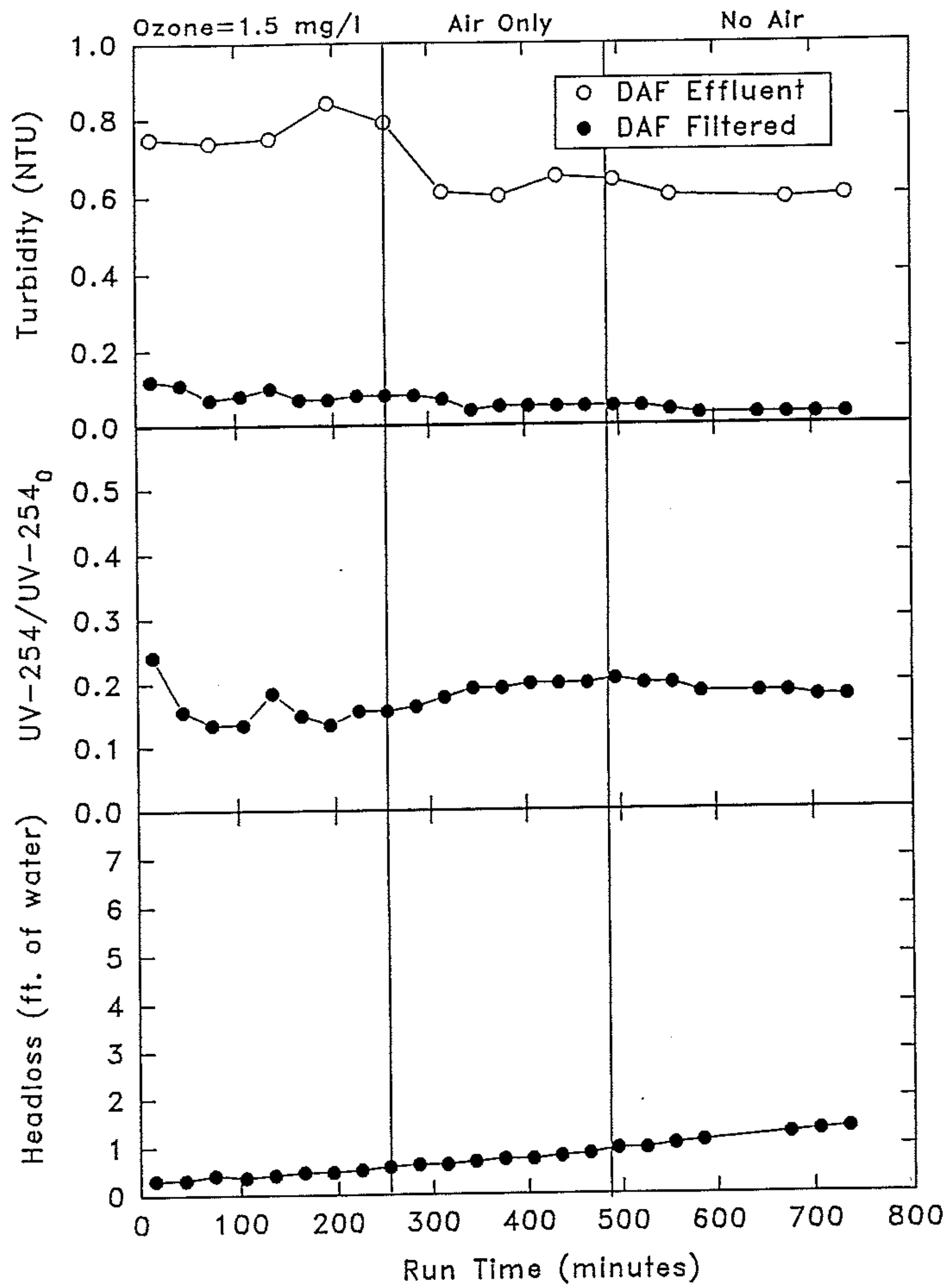


Figure 4.22 DAF and Filtered Water Quality; Run #15, Ozone vs No Air vs No Air/No Ozone

application. Average clarified water (after DAF) turbidity was slightly higher for the pre-ozonation condition (0.77 ntu) than the air only (0.62 ntu) and no air/no ozone conditions (0.60 ntu). Average filtered water turbidity decreased slightly as ozonation conditions changed from ozone (0.07 ntu) , to air only (0.05 ntu), and to no air/no ozone (0.03 ntu). The impact of ozonation on filtered water UV254 values was slightly favorable. The average fractions of raw water UV254 for ozone, air only and no air/no ozone conditions were 85, 80 and 82 percent. The test conditions were not evaluated sufficiently long to evaluate slight changes in headloss development. No significant changes in headloss development occurred as a result of the changing ozonation conditions.

Turbidity, UV254 and pH across treatment were measured twice for each condition during run #15; average values are presented in Table 4.26. The turbidity of the raw water did not change after pre-ozonation. However, the UV254 after ozonation was 79 percent of the raw water UV254. After flotation, UV254 removal was slightly greater for the pre-ozonation condition than for the air only and no air/no ozone conditions (81 percent vs 76 percent vs 77 percent).

DOC across treatment was measured once for each ozonation condition during run #15 (see Figure 4.23). Pre-ozonation had no significant effect on the measured raw water DOC. For all three ozonation conditions, flotation removed 50-55 percent of the raw water DOC and filtration removed an additional 5-10 percent. DOC values after flotation and after filtration decrease slightly as the conditions changed from pre-ozonation to air only and to no air/no ozone, but the differences are not considered significant.

Table 4.26 Turbidity, UV254 and pH Across Treatment; Run #15, Evaluation of Pre-Ozonation

Location	Turbidity (ntu)			UV254 (cm^{-1})		
	O_3 On	Air	No Air	O_3 On	Air	No Air
Raw Water	1.53	1.65	1.67	0.139	0.139	0.144
Ozone-Pre	1.53	1.71	1.67	0.110	0.136	0.142
Floc	3.5	3.5	3.9	--	--	--
DAF Effl	0.80	0.62	0.60	0.026	0.034	0.033
DAF Filt	0.07	0.05	0.03	0.021	0.028	0.026

Location	pH		
	O_3 On	Air Only	No Air/ No Ozone
Raw Water	6.7	6.7	6.7
Ozone-Pre	6.7	6.7	6.7
Floc	6.5	6.6	6.5
DAF Effl	6.5	6.6	6.5
DAF Filt	6.5	6.6	6.5

Note: Values represent averages of two measurements

Total particle counts, particle number average diameters and particle volume average diameters across treatment for run #15 are presented in Table 4.27. Measurements were taken once for each ozonation condition. Values labeled "ozone-pre" represent measurements of samples taken after the ozone contactor. For the no air/no ozone condition, the "ozone-pre" value acts as a control because it should be the same as the raw water value. No significant changes in raw water particle number or average diameter were observed as a direct result of pre-ozonation. For

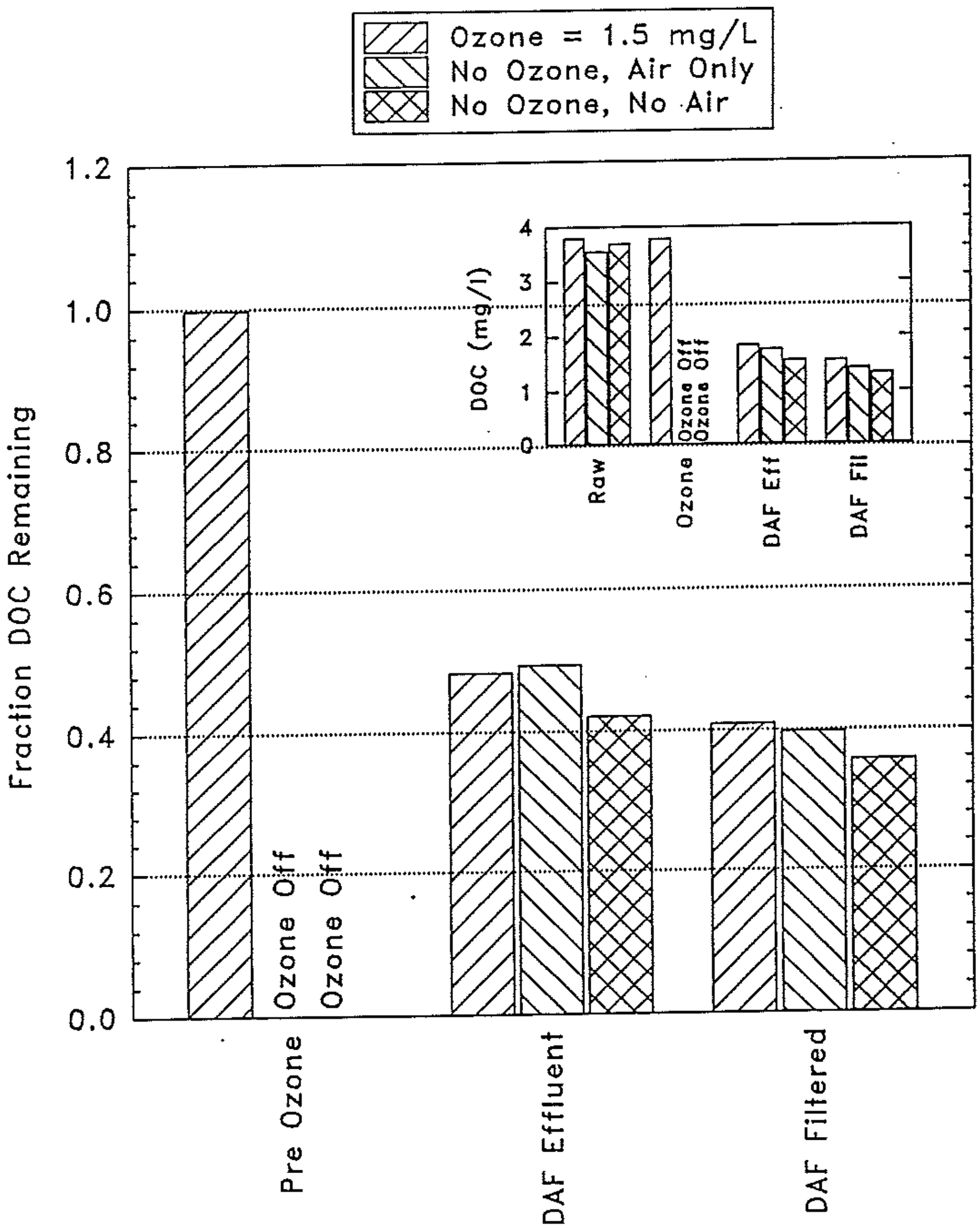


Figure 4.23 DOC Results for Run #15

the pre-ozonation, air only and no air/no ozone conditions respectively, total particle counts of raw water were 7571 /mL, 8709 /mL and 9663 /mL and after the ozone contactor were 7310 /mL, 7086 /mL and 8310 /mL. Also, pre-ozonation and air only had no significant effects on particle removal by flotation. Particle counts after filtration were slightly lower for pre-ozonation (72 /mL) than for air only and no ozone/no air (173 /mL and 159 /mL respectively).

Table 4.27 Particle Counts Across Treatment; Run #15, Evaluation of Pre-Ozonation

Location	Total Particles (#/mL)		
	O_3 on	Air Only	No Air/No Ozone
Raw Water	7571	8709	9663
Ozone-Pre	7310	7086	8310
Floc	2784	2589	2326
DAF Effl	956	944	1158
DAF Filt	72	173	159

Location	Number Average Diameter (μm)			Volume Average Diameter (μm)		
	O_3 on	Air	No Air	O_3 on	Air	No Air
Raw Water	3.9	3.4	3.4	5.4	4.8	5.6
Ozone-Pre	3.9	4.0	3.6	6.2	5.6	5.2
Floc	5.3	5.4	4.3	13.8	14.1	12.0
DAF Effl	3.7	3.5	3.5	6.1	5.7	6.7
DAF Filt	3.5	3.2	2.9	8.5	4.8	3.7

4.1.6.4 Pre-Ozonation vs No Ozonation: Run # 18

Run #18, performed on October 23-24, 1992, evaluated the effects of pre-ozonation on flotation and filtration following flotation compared to no ozone. Results are presented for both the DAF and the direct filtration (DF) pilot trains. Pre-ozonation at a dose of 1.5 mg/L was practiced on both trains for several days prior to the run. Unlike the other 19 runs performed, the filters were not backwashed prior to data collection for run #18. The pre-ozonation condition was observed for 4 hours before the ozone generators were shut down. The no ozone condition was observed for 3 hours, allowed to run overnight, and observed for another two hours. The filter on the DF train backwashed automatically overnight.

Operating conditions, coagulant dosages and raw water quality data for run #18 are presented in Table 4.28. Caustic was not applied to either train to eliminate one of the "variables" between the two trains. Also, the filtration rate on the DAF train was 4.5 gpm/ft^2 compared to 3.0 gpm/ft^2 on the DF train. The turbidity of the raw water changed slightly from 1.6 ntu at the beginning of the run to 2.3 toward the end of the run. (Table 4.28).

Filtered water turbidity and fraction of raw water UV254 removals, ozonated effluent turbidity and fraction of raw water UV254, and filter headloss data for the DF and DAF pilot trains are presented in Figure 4.24. DAF filtered water turbidity averaged 0.08 ntu with pre-ozonation and decreased to an average of 0.03 ntu without ozonation. Pre-ozonation had no observable effect on DF filtered water turbidity as measured by turbidities of 0.02 ntu with and without pre-ozonation. For both trains, the pre-ozonation condition resulted in slightly higher UV254 removals than without

Table 4.28 Operating Conditions, Dosages, and Raw Water Data; Run #18 Evaluation of Pre-Ozonation

Parameter	Run #18-DAF (10/23/92-10/24/92)	Run #18-DF (10/23/92-10/24/92)
Operating Conditions		
Recycle Ratio (%)	8.0	N/A
Sludge Removal Freq. (1/# hr)	1 / 3 hrs	N/A
Filter Loading (gpm/ft^2)	4.5	3.0
Flocculation Time (min)	16	N/A
Chemical and Ozone Dosages		
Ferric Chloride (mg/L)	7.9	7.2
Polymer (mg/L)	2.2	2.2
Caustic (mg/L)	0.0	0.0
Ozone (mg/L)	1.5-Pre; No Ozone	1.5-Pre; No Ozone
Raw Water Characteristics		
Turbidity (ntu)	2.0 (1.58-2.3)	2.0 (1.58-2.3)
UV254 (cm^{-1})	0.112 (0.107-0.116)	0.112 (0.107-0.116)
pH	6.8 (6.7-6.9)	6.8 (6.7-6.9)

pre-ozonation but the effect was slightly more significant for the DF train than the DAF train. Without pre-ozonation, the two trains removed equal percentages of UV254. Average UV254 removals with pre-ozonation and without pre-ozonation were 80 and 76 percent respectively for the DAF train, and were 83 and 76 percent respectively for the DF train. The fraction of raw water UV254 after ozonation was slightly higher for the DAF train (81 percent) than the DF train (77 percent).

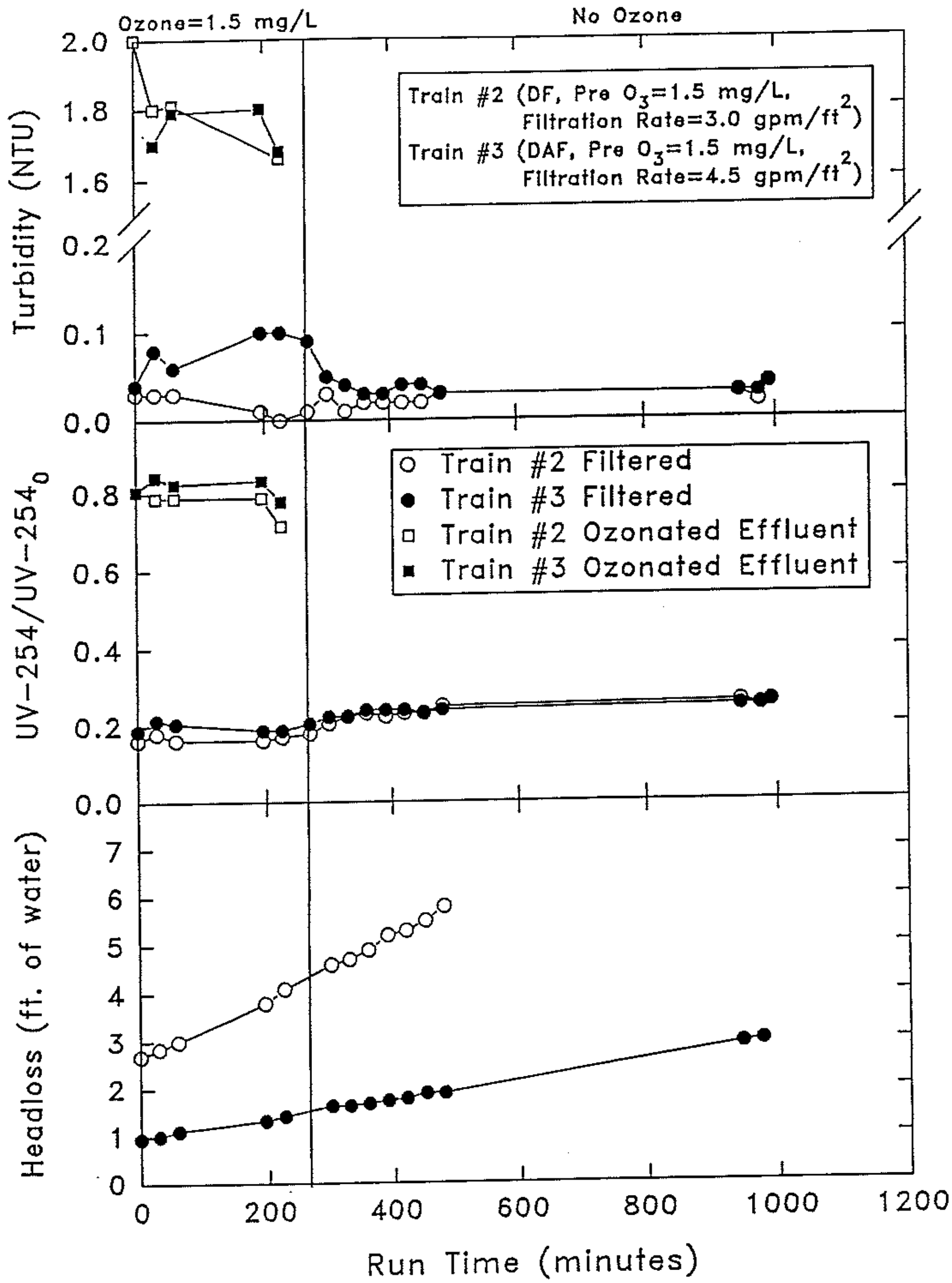


Figure 4.24 **Filtered and After Ozonation Water Quality; Run #18, Ozone vs No Air/No Ozone**

Sufficient data were not collected to measure small changes in headloss development between the two conditions examined. However, examination of Figure 4.24 shows that pre-ozonation had no significant effect on filter headloss development compared to no ozonation for either pilot train.

Turbidity, UV254 and pH across treatment were measured twice for each condition during run #18; average values are presented in Table 4.29. Pre-ozonation

Table 4.29 Turbidity, UV254 and pH Across Treatment; Run #18, Evaluation of Pre-Ozonation

Location	Turbidity				UV254			
	DAF		DF		DAF		DF	
	O_3	No O_3	O_3	No O_3	O_3	No O_3	O_3	No O_3
Raw Water	1.74	2.3	1.74	2.3	0.116	0.108	0.116	0.108
Ozone-Pre	1.80	Off	2.0	Off	0.092	Off	0.066	Off
Floc	3.7	3.2	--	--	--	--	--	--
DAF Effl	0.93	0.67	--	--	0.025	0.030	--	--
DAF Filt	0.07	0.04	0.02	0.03	0.021	0.028	0.018	0.028

Location	pH			
	DAF		DF	
	O_3	No O_3	O_3	No O_3
Raw Water	6.8	6.8	6.8	6.8
Ozone-Pre	6.8	Off	6.8	Off
Floc	6.4	6.3	6.4	6.3
DAF Effl	6.6	6.3	--	--
DAF Filt	6.5	6.3	6.6	6.4

had a slightly negative impact on flotation performance as measured by clarified turbidities of 0.93 ntu with pre-ozonation and 0.76 ntu without pre-ozonation. Pre-ozonation had a positive effect on UV254 removal through flotation as measured by 78 percent removal with pre-ozonation and 72 percent without.

Two DOC samples were taken on both trains across treatment at one time for each condition evaluated during run #18. DOC results are presented in Figure 4.25. Pre-ozonation did not significantly alter the measured amount of raw water DOC for the DAF train (100 percent of raw water) and slightly reduced the DOC on the DF train (96 percent of raw water remaining). With pre-ozonation, the DF train filters removed 38 percent of raw water DOC, and on the DAF train, flotation removed 47 percent of raw water DOC and subsequent filtration removed an addition 8 percent. DOC removals across treatment (i.e., DF filtered water, DAF clarified water, and DAF filtered water) were 2-6 percent higher with pre-ozonation than without.

Particle counts of the filtered water for both trains were measured once for each condition. With pre-ozonation, the DAF filtered water contained 22 /mL total particles and the DF filtered water contained 43 /mL. Without pre-ozonation, the DAF and DF filtered water total particle counts were 34 /mL and 38 /mL respectively.

4.1.6.5 Discussion

Intermediate-ozonation resulted in successful treatment as measured by filtered water turbidity, UV254, filter headloss development and particle counts during run #1. Intermediate ozonation directly reduced the UV254 of water after flotation. Comparison of run #1 (intermediate-ozonation) and run #2 (no ozonation) showed

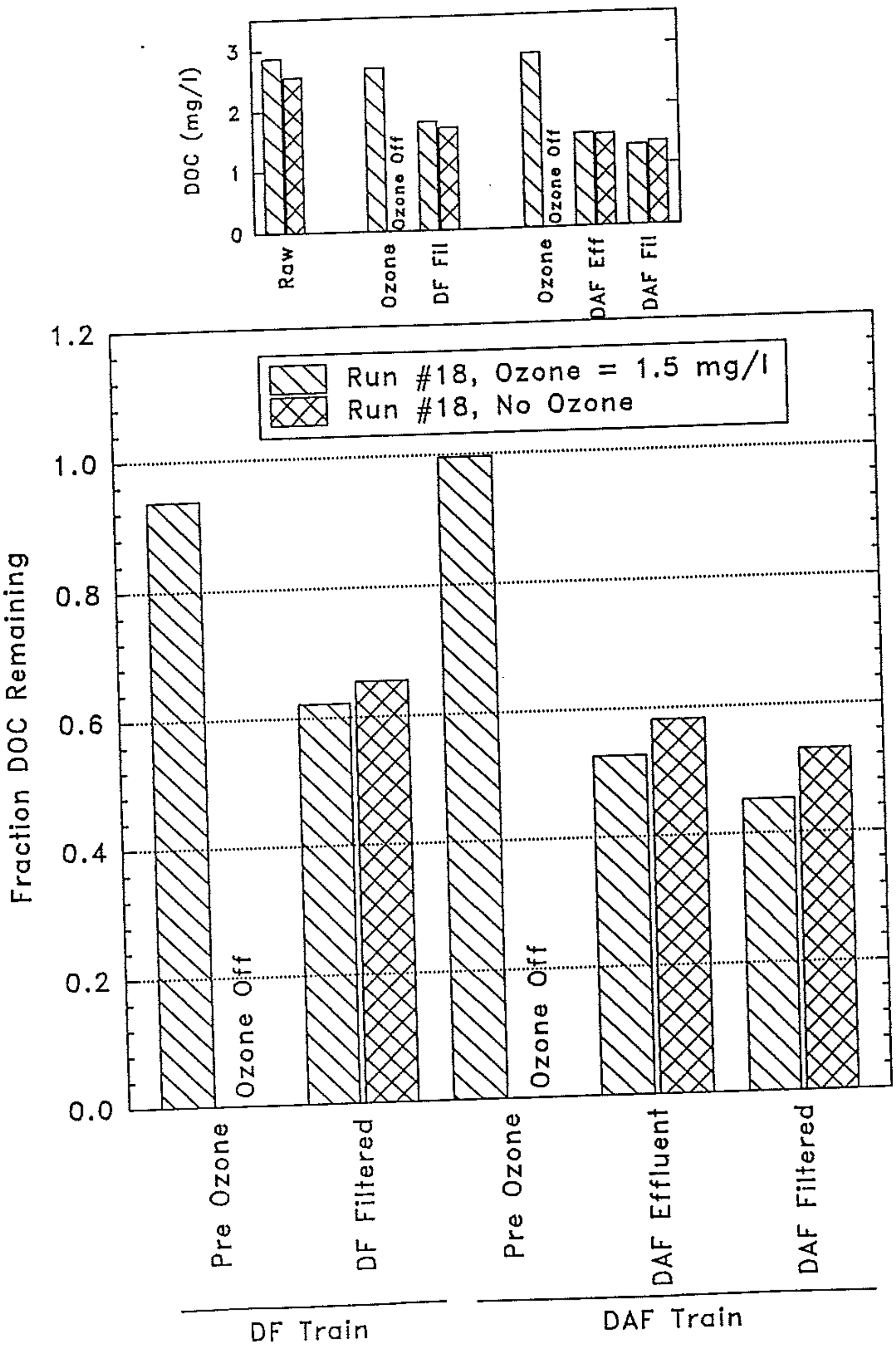


Figure 4.25 DOC Results for Run #18

lower filtered water UV254 with intermediate-ozonation than without. However, intermediate ozonation showed no significant effects on DOC removals through treatment compared to no ozonation. During run #5 and the beginning of run #6, intermediate ozonation resulted in unacceptable filtered water turbidities of 0.4-0.5 ntu. The data suggest oxidation and subsequent precipitation of manganese with intermediate ozonation. Without further coagulant addition, the precipitate is not removed through filtration resulting in increased turbidity levels.

Pre-ozonation resulted in effective treatment on the DAF pilot plant throughout 1992. Results from runs #15 and #18 show pre-ozonation (compared to no ozonation) resulted in improved removal of UV254 through treatment (i.e. filtered waters) and resulted in higher filtered water turbidity levels. Removal of UV254 by flotation increased with pre-ozonation and clarified water turbidities were similar with pre-ozonation and without. Pre-ozonation reduced the UV254 of raw water by approximately 19-23 percent but did not affect the measured quantity of DOC.

4.2 General DAF Performance and Comparison with DF and the WRTP

This section contains an evaluation of treatment performance of the DAF pilot train with comparisons to the DF pilot train and the WRTP. Results are presented in terms of turbidity, UV254 and DOC measured across treatment on various sample dates. Also presented are results from continuous monitoring of filter headloss development with a brief discussion of filter performance of the pilot and full scale plants.

4.2.1 General Water Quality

Turbidity results for several sample dates for the pilot trains and for the full scale plant are shown in Figure 4.26. For the DAF pilot train, the raw water turbidity of approximately 1.1 ntu increased to 2.5-3.5 ntu by coagulation and flocculation. Flotation typically produced clarified turbidities of 0.6-0.9 ntu, with a 1992 average of 0.74. Filtration following flotation produced water with an average turbidity of 0.05 ntu and consistently less than 0.1 ntu. Overall, filtered water turbidity for the DAF train was 0.01-0.03 ntu higher than the direct filtration train and the full scale plant. Possible explanations for this difference are: 1) the coagulant dosage of the DAF pilot train compared to the direct filtration train was not optimized due to time constraints; 2) the full scale and pilot plants were run on the low side of optimum coagulant conditions for the direct filtration process and the dilution caused by the eight percent recycle of air saturated water into the flotation tank may have caused less effective particle charge neutralization and therefore less effective particle removal; 3) given good flotation performance and therefore fewer particles applied to the filters, filter ripening may have taken longer on the DAF train; and 4) slight deviations from optimum steady state may have occurred during the summer due to DAF runs with varying operation (flocculation times, filter hydraulic loading rates, location of ozone, etc.) while the direct filtration train was run in a constant mode at 3.0 gpm/ft^2.

Figure 4.27 presents UV254 measurements across treatment on various sample days in 1992. As discussed previously, pre-ozonation reduces raw water UV254 by 20 to 30 percent. The DAF and DF pilot plants achieved average overall UV254

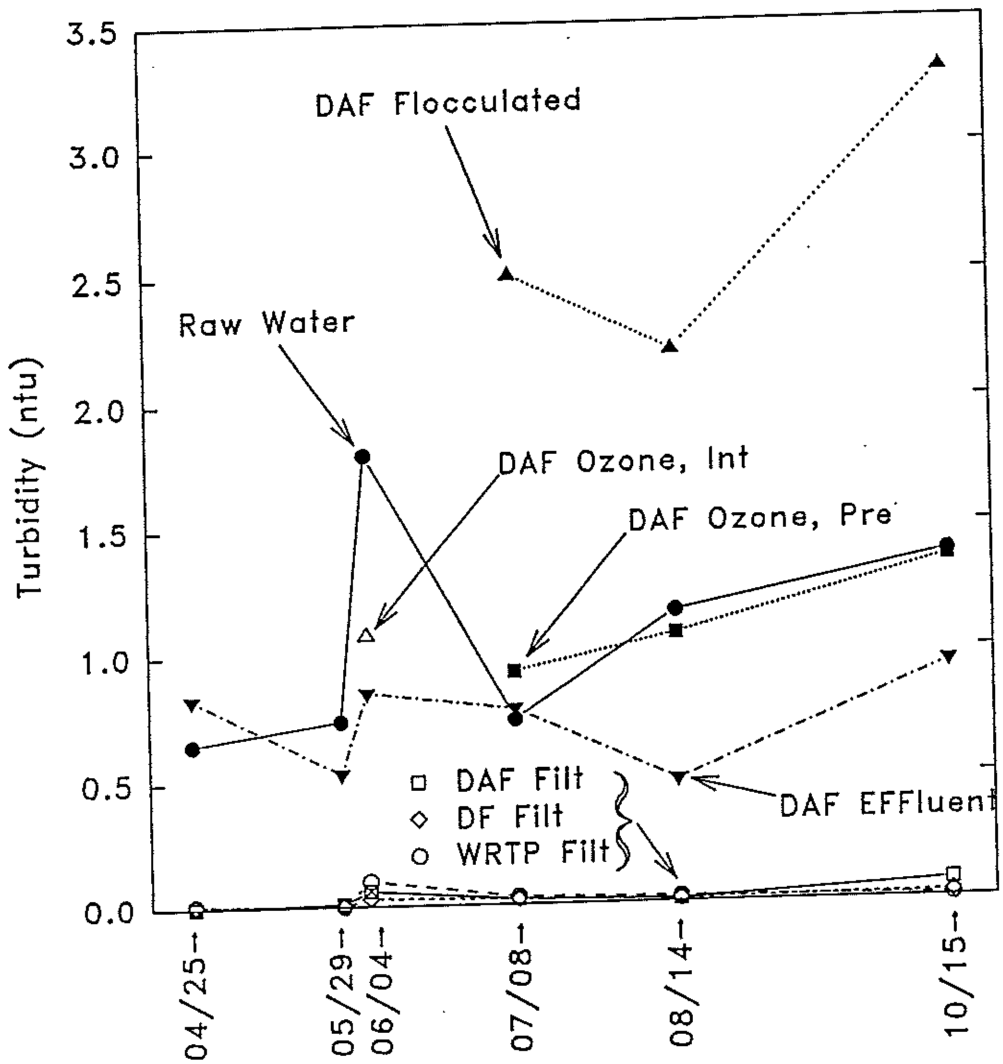


Figure 4.26 Turbidity for Various Sampling Days in 1992

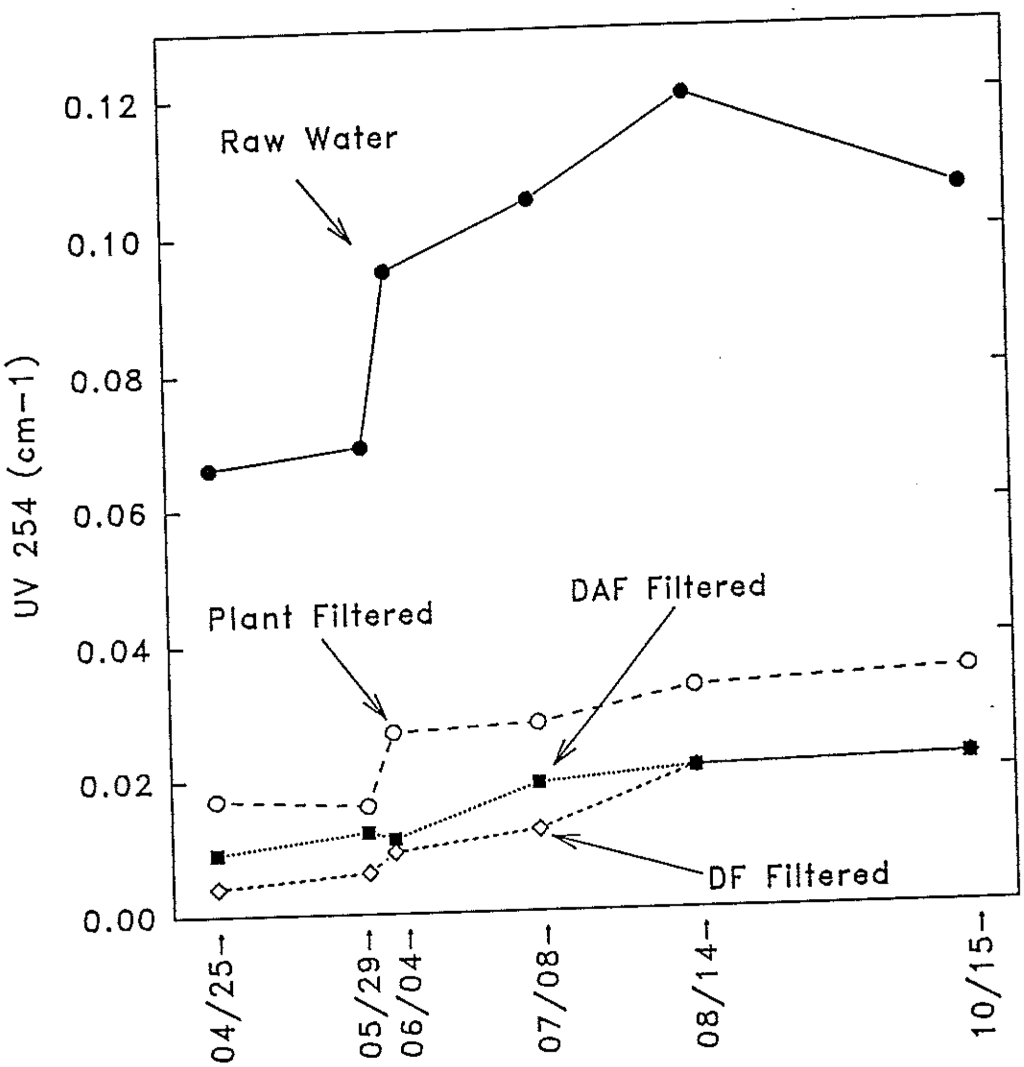


Figure 4.27 UV254 for Various Sampling Days in 1992

removals of 84 and 88 percent respectively. The difference between DAF and DF is primarily attributed to differences in ozone application on the two trains. Treatment through both pilot trains was more effective than the full scale plant, which removed 67 percent of the UV254. Pre-ozonation and biodegradation in the GAC/sand filters are the most likely causes of the more effective UV254 removal in the pilot trains.

Results of DOC analysis are presented in graphical form in Figure 4.28 and tabular form in Table 4.30. The DOC results follow similar trends as observed for the UV254. However, removals across treatment are greater for UV254 than DOC (84% vs 49% for the DAF train). Greater removal of UV254 as compared to DOC is expected because UV measures the more hydrophobic organic matter that tends to be easily removed by coagulation. On average, flotation following coagulation removed 45-50 percent of the raw water DOC, which is very similar to the West River treatment plant performance. Filtration following flotation removed an additional 5-10 percent of the raw water DOC. The parallel DAF and DF trains performed very similarly with respect to DOC removal. Biodegradation is the most likely cause of the additional DOC removal by the DAF train filter. This conclusion is consistent with previous work at West River where DOC levels in GAC/sand filtered waters were lower than levels for anthracite/sand filters (Reckhow *et al.*, 1992, Tobiason *et al.*, 1993a).

4.2.2 Filter Performance

Filter headloss development was recorded on a continuous basis on both the direct filtration and DAF pilot trains to evaluate filter performance. In addition, runs

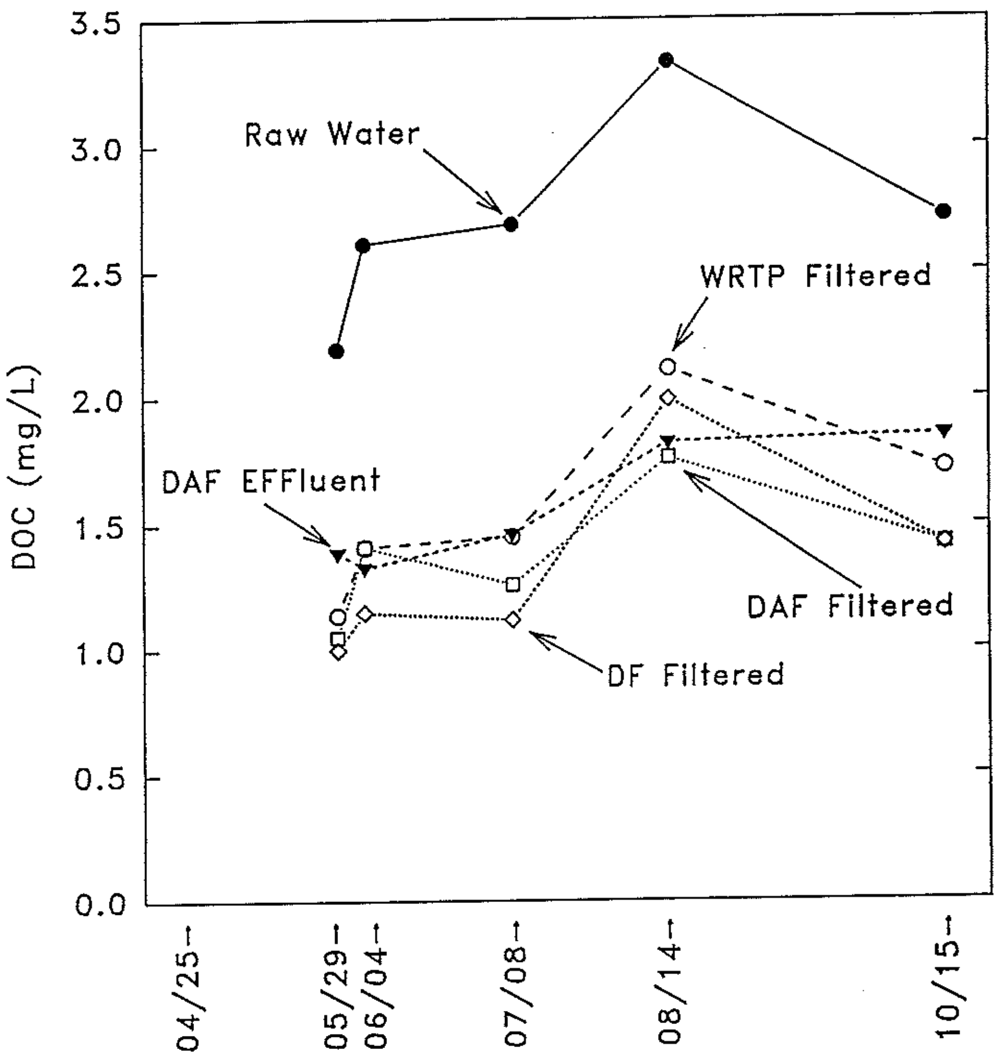


Figure 4.28 DOC for Various Sampling Days During 1992

Table 4.30 DOC on Various Sample Dates

DOC (mg/L)					
	Sample Date				
Sample	05/29	06/04	07/08	08/14	10/15
Raw Water	2.2	2.6	2.7	3.3	2.7
DAF Pilot Plant					
Pre Ozone	off	off	2.5	3.2	2.9
After DAF	1.4	1.3	1.5	1.8	1.9
Int Ozone	off	1.4	off	off	off
Filtered	1.1	1.4	1.3	1.8	1.4
DF Pilot Plant					
Pre Ozone	2.1	2.5	2.5	3.3	3.1
Filtered	1.0	1.2	1.1	2.0	1.4
West River Plant					
Filtered	1.1	1.4	1.5	2.1	1.7

#8, #9, and #10 evaluated the performance of the DAF pilot train at increased filter loading rates. Section 4.1.3 presents the effects of increased filter loading rate on overall DAF train performance during runs #8, #9 and #10. This section will present a comparison of DF and DAF train filter performance during runs #8 and #10. Unit filter run volumes (UFRVs) for the DF and DAF pilot trains are also presented for all twenty pilot "runs" and as monthly averages from daily UFRV data. The UFRV is the total amount of water treated, per surface area of the filter, for one run and is reported as gallons per square foot of filter surface area per one run.

4.2.2.1 Increased Filter Loading, DF and DAF: Pilot Runs #8 and #10

Run #8, performed on July 8, 1992 evaluated the DF and DAF pilot trains at filter loading rates of 3.0 gpm/ft^2. Run #10, performed on July 10, 1992 evaluated the DF pilot train at a filter loading rate of 3.0 gpm/ft^2 and the DAF pilot train at 6.0 gpm/ft^2. Filtered water turbidity, fraction of raw water UV254 and filter headloss versus time for run #8 are presented in Figure 4.29 and in Figure 4.30 for run #10.

Finished water quality during both runs was similar between the DF train and the DAF train, with turbidity consistently below 0.08 ntu and UV254 removals above 75 percent. During run #8, with both trains at the same filter loading rate, the filter headloss rate on the DF train was three times the rate on the DAF train (3.8 in/hr versus 1.4 in/hr). During run #10, with the DAF train at twice the filter loading rate as the DF train filter, the rate of headloss development on the DF train filter was slightly higher than the headloss development on the DAF train filter (3.9 in/hr versus 3.5 in/hr). As expected, the empty bed filter headloss was higher for the DAF train at a filter loading rate of 6.0 gpm/ft^2 than the DF train at 3.0 gpm/ft^2 (13 inches versus 5 inches). Projecting to eight feet of headloss, the unit filter run volumes are 12100 and 8400 gal/ft^2/run for the DAF train and 4300 and 4100 gal/ft^2/run for the DF train during run #8 and run #10 respectively.

4.2.2.2 UFRVs of Pilot Runs and Monthly Averages

Table 4.31 contains the hydraulic filter loading rate and the calculated UFRVs on both pilot trains for all twenty runs. The UFRVs in Table 4.31 are calculated to eight feet of headloss from available data. The UFRVs on the DAF train were two to

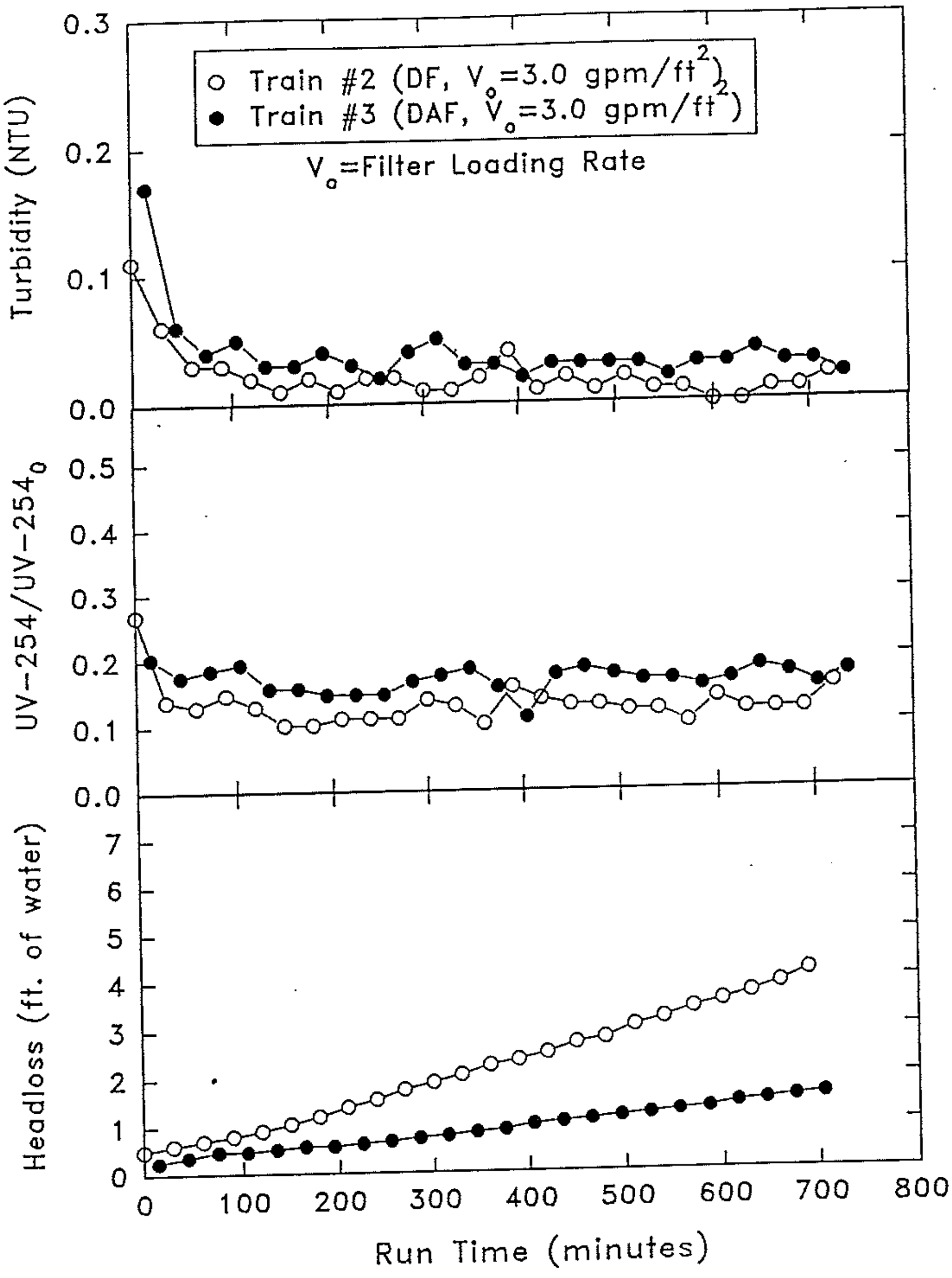


Figure 4.29 Filtered Water Quality; DF and DAF Trains; Run #8

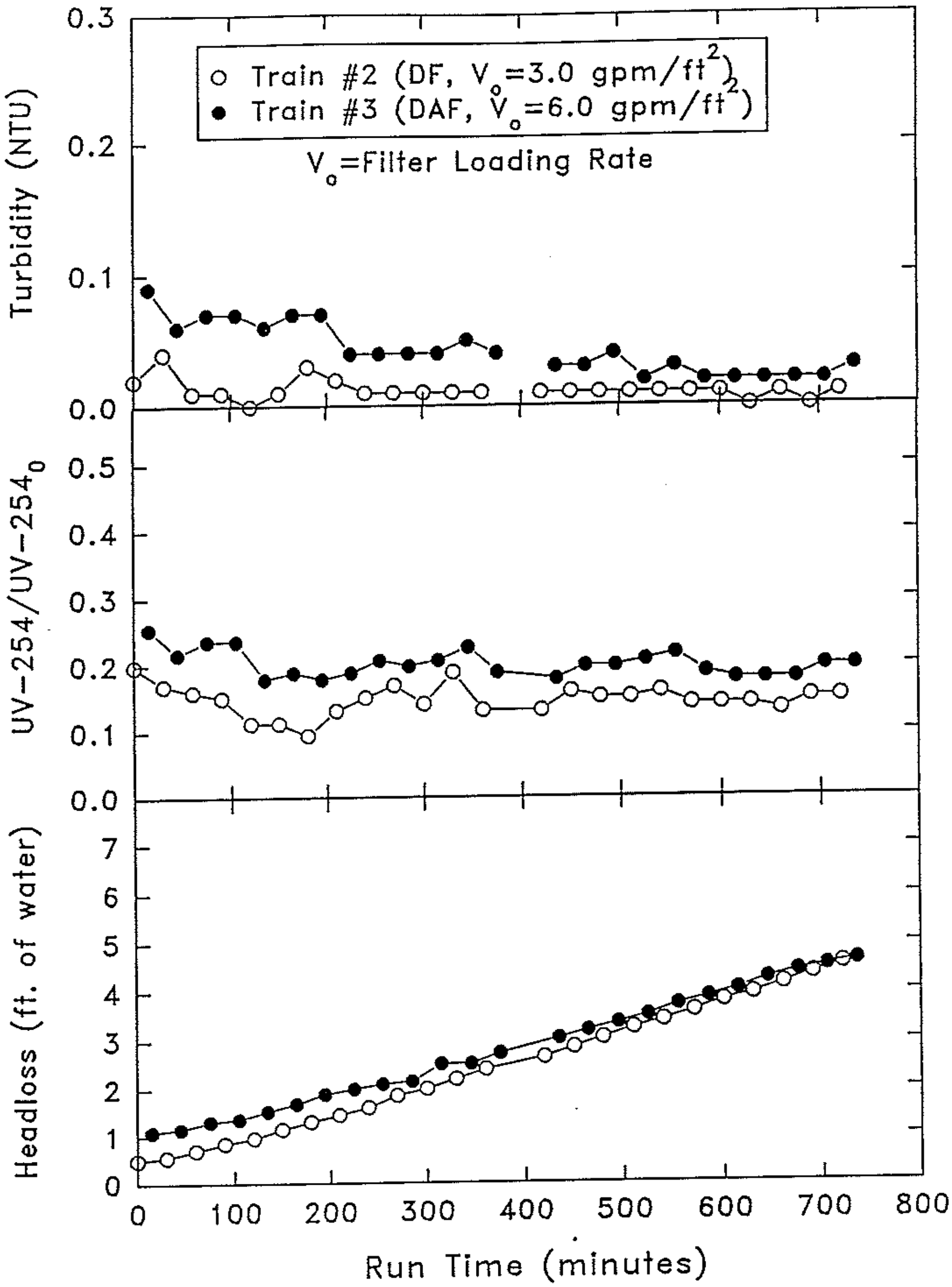


Figure 4.30 Filtered Water Quality; DF and DAF Trains; Run #10

Table 4.31 Projected UFRVs for Runs Performed During 1992

RUN #	Train #2, DF V_o (gpm/ft^2)	Train #2, DF UFRV (gal/ft^2/run)	Train #3, DAF V_o (gpm/ft^2)	Train #3, DAF UFRV (gal/ft^2/run)
1	3.0	3,000	3.0	27,400
2	3.0	3,700	3.0	18,200
3	3.0	--	3.0	8,800
4	3.0	4,600	3.0	9,100
5	3.0	--	3.0	--
6	3.0	--	3.0	18,200
7	3.0	--	3.0	16,300
8	3.0	4,300	3.0	12,100
9	3.0	3,900	4.5	8,800
10	3.0	4,100	6.0	8,400
11	3.0	--	3.0	10,300
12	3.0	1,900	3.0	13,200 GAC
			3.0	7,300 Anth
13	3.0	2,200	3.0	5,900
14	3.0	2,300	3.0	7,800
15	3.0	--	3.0	15,800
16	3.0	3,300	4.5	5,100
17	3.0	2,800	4.5	9,200
18	3.0	3,400	4.5	15,800
19	3.0	4,600	4.5	24,600
20	3.0	4,000	4.5	16,400

Note: Unit filter run volumes are projected to 8 feet of total head loss from available data five times the UFRVs on the DF train and on average were 3.8 times higher on the DAF train (13,200 gal/ft^2/run versus 3400 gal/ft^2/run).

Figure 4.31 shows monthly average UFRVs for the DF and DAF pilot plants and the WRTP. Examination of Figure 4.31 shows the DAF pilot train had an average UFRV 3.2 times that of the DF pilot train and 3.6 times that of the WRTP (10200 gal/sq ft/run vs 3200 gal/sq ft/run vs 2800 gal/sq ft/run). Through most of the study, both the DF and DAF pilot plants were operated at a filter hydraulic loading of 3.0 gpm/sq ft. At the same filter hydraulic loading rate, a tripling of UFRV by DAF corresponds to a filter run time on the DAF train three times the filter run time on the DF train.

4.2.2.3 Discussion

During run #8 and on average during 1992, comparison of the DAF and DF trains at filter hydraulic loading rates of 3.0 gpm/ft^2 shows that particle removal by DAF decreased filter headloss development such that the filter run times were typically three time longer on the DAF train. The DAF train also performed well at filter loading rates as high as 6.0 gpm/ft^2, both with respect to finished water quality and filter run time, compared to the DF train at a filtration rate of 3.0 gpm/ft^2.

The West River treatment plant currently experiences short filter runs during periods of poor raw water quality, particularly during periods of high algae. Short filter runs result in high water loss due to backwashing and limit the ability to increase the hydraulic loading to the filters. The addition of DAF prior to filtration would allow for less water loss due to backwashing, longer filter run times and the ability to increase plant capacity by increasing the hydraulic loading rate to the filters.

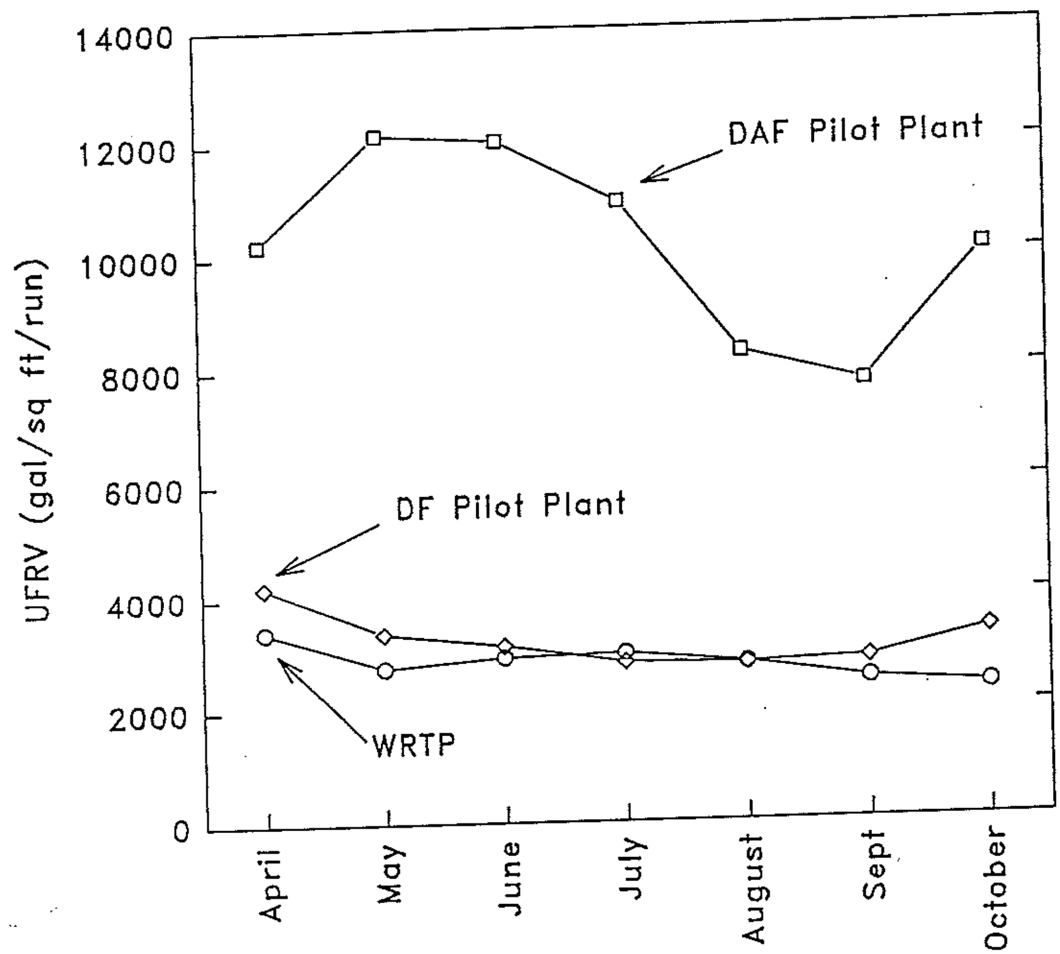


Figure 4.31 Average Unit Filter Run Volumes for the DF, DAF Pilot and WRTP Plants

CHAPTER V

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Coagulation using ferric chloride in conjunction with a cationic polymer and using ferric chloride alone was successful when used in conjunction with flocculation, flotation and filtration. Ferric chloride and cationic polymer doses used by the in-line direct filtration WRTP (i.e. 8-10 mg/L $FeCl_3$, 1-2 mg/L polymer (as polymer)) provided effective treatment by DAF. Without polymer, the ferric chloride dose for effective treatment was twice the required ferric chloride dose with 1-2 mg/L of polymer (i.e. 16-20 mg/L).

Coagulation with ferric chloride alone resulted in slightly higher filter headloss development as compared to coagulation with ferric chloride with polymer. Turbidity values after DAF were slightly lower when ferric chloride with polymer was used than with ferric chloride alone. Filtered water turbidity, UV254, DOC and particle counts were similar for both coagulant conditions. The approximate cost for primary coagulants for a typical ferric chloride and polymer dosage is $0.022/1000 gallons and is $0.009/1000 gallons for a typical ferric chloride alone dose.

Flotation and subsequent filtration provided effective treatment at recycle ratios of 9.5 and 8.0 percent. At 6.0 and 5.0 percent recycle ratios, clogging of the needle valves resulted in less effective particulate removal by DAF causing increased filter headloss development. Proper design of the needle valves for low recycle flows would be expected to improve DAF performance at low recycle.

Solids removal by DAF prior to filtration allowed for a doubling of the hydraulic loading rate to the filters while maintaining treated water quality. The filter headloss development on the DAF train at a filter loading of 6.0 gpm/ft^2 was similar to filter headloss development on the parallel DF train at a filter loading of 3.0 gpm/ft^2.

The average unit filter run volume (UFRV) for the DAF pilot train was three times that of the DF pilot train and the WRTP. For the same filter hydraulic loading rates on the DAF and DF trains, this corresponds to filter run times on the DAF train three times the filter run times on the DF train.

Sludge removal was provided by intermittent operation of a full length mechanical scraper with rubber paddles. Accumulation of the sludge for up to eight hours (i.e. sludge removal frequency of once per eight hours) resulted in no deterioration in DAF clarified or filtered water quality. After 24 hours of sludge accumulation, large visible flocs were observed in the DAF effluent. Decreasing the sludge removal frequency increased the percent solids of the sludge produced.

Flocculation times of eight and sixteen minutes prior to flotation resulted in effective treatment of West River source water. Finished water quality was similar for both flocculation conditions as measured by turbidity, UV254, DOC, and particle counts. During one set of runs, sixteen minutes of flocculation time resulted in higher headloss development than eight minutes of flocculation time. However, later in the year headloss results were opposite those observed earlier.

Particle count analyses of the flocculation sample showed eight minutes of contact time in the flocculation chamber resulted in more numerous and smaller particles compared to sixteen minutes. The shift toward smaller flocculated particles caused by the shorter flocculation time resulted in decreased particulate removal by DAF.

Use of intermediate ozonation produced mixed results. During one comparison, intermediate ozonation had no significant effects on overall treatment except for a reduction in UV254 through treatment. Treatment a few days later with intermediate ozonation resulted in unacceptable filtered water turbidities of 0.4-0.5 ntu. The data suggest oxidation and subsequent precipitation of manganese with intermediate ozonation. Without further coagulant addition, the precipitate is not removed through filtration resulting in increased turbidity levels.

DAF used in conjunction with pre-ozonation produced effective results throughout 1992. Pre-ozonation reduced the UV254 of raw water by approximately 19-23 percent and did not affect the quantity of DOC entering the DAF process. After flotation and filtration, UV254 levels were lower with pre-ozonation than without. DOC values were similar regardless of ozone application. Pre-ozonation resulted in slightly increased turbidity levels after filtration than without ozonation.

Treatment by DAF produced a finished water similar in quality to treatment by the DF pilot train and the WRTP. The DAF pilot plant produced water with an average turbidity of 0.05 ntu and consistently below 0.1 ntu. Overall, filtered water turbidity for the DAF train was 0.01-0.03 ntu higher than the direct filtration train and the full scale plant. The DAF and DF pilot plants achieved average overall UV254 removals of 84 and 88 percent respectively through 1992. Treatment through both pilot trains was more effective than the full scale plant, which removed 67 percent of the UV254. Pre-ozonation and biodegradation in the GAC/sand filters are the most likely causes of the more effective UV254 removal in the pilot trains. On average, flotation following coagulation removed 45-50 percent of the raw water DOC. Filtration following flotation removed an additional 5-10 percent of the raw water DOC. The parallel DAF and DF trains performed very similarly with respect to DOC removal. Biodegradation is the most likely cause of the additional DOC removal by the DAF train filter as compared to the full scale WRTP.

5.2 Recommendations

If the WRTP were to add flocculation and flotation prior to filtration, solids removal by flotation could allow an increase in the hydraulic filter loading rates to increase plant capacity. Coagulation using ferric chloride alone or ferric chloride with polymer would provide acceptable results. Studies evaluating flocculation times and coagulant conditions at cold temperature should be conducted to verify the results during warm water conditions.

Coagulation conditions similar to the WRTP were used throughout this study. Evaluation of the effects of coagulation conditions such as pH, coagulant dose and further evaluation of alternative coagulant types should be performed to optimize DAF treatment. The fate of manganese throughout the DAF treatment process should be studied, particularly with respect to the two ozonation options evaluated.

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